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Coal Gasification Environmental Data Summary: Solid Wastes and By-Product Tars

Radian Corp., Austin, TX

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ABSTRACT

This report is one of several planned data summary reports on environmental aspects and pollutants specific to coal gasification. It addresses characteristics of solid wastes (ash and cyclone dust) and by-product tars and oils analyzed in nine prior EPA source tests and evaluation studies and limited other data. The specific objectives of this report were to compile and summarize solid waste properties and identify behavioral trends. The results of this data compilation showed that gasifier ash and cyclone dust are nonhazardous under RCRA and negative according to selected bioassay tests. However, ash compositions differed with different processes, operating conditions, and feedstocks. Tars and oils are more likely to pose environmental problems due to detectable concentrations of polynuclear aromatic compounds, other toxic and carcinogenic organic compounds, and entrained trace elements. However, high heating values of tars and oils make them candidates to be used as fuels if the inorganic residues are treated properly. Engineering properties and leaching properties of gasifier solid wastes are not sufficiently defined to allow a good evaluation of disposal alternatives.

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SECTION 1

INTRODUCTION

During the past decade, the Environmental Protection Agency (EPA) has conducted numerous data acquisition studies at synthetic fuel facilities in order to characterize the different processes and discharge streams. These data have been used to evaluate applicable control technologies and to estimate potential discharge characteristics from commercial plants. Compilation of EPA's Environmental Assessment data allows identification of potential environmental problems and special monitoring needs for specific synfuels processes. Under the Energy Security Act, the EPA will use these Environmental Assessments to advise on the adequacy of proposed Environmental Monitoring Plans and participate in Monitoring Review Committees for projects receiving financial assistance from the Synthetic Fuels Corporation (SFC).

This report is one of several planned data summary reports on environmental aspects and pollutants specific to coal gasification. It addresses characteristics of solid wastes (ash and cyclone dust) and by-product tars and oils from synthetic fuel facilities studied by the U.S. EPA and others (1-22). The facilities discussed here were selected on the basis of greater availability of process, gas, liquid, and solid phase data. These processes include:

- Chapman (low-Btu),
- Two Wellman-Galusha (low-Btu),

- Riley Gas Producer (low-Btu),
- Foster-Wheeler/STOIC (low-Btu),
- Lurgi-type (medium-Btu),
- Kellogg-Rust/Westinghouse (medium-Btu) (funded by the Gas Research Institute),
- Two Koppers-Totzek (medium-Btu), and
- Texaco (medium-Btu) [jointly funded by EPA, Tennessee Valley Authority (TVA) and Electric Power Research Institute (EPRI)].

Three major objectives are accomplished in this report: (1) compilation and summary of characteristics of solid wastes and solid streams--ash, cyclone dust, and by-product tar and oil from gasifiers; (2) evaluation of behavioral trends in data with respect to processes; and (3) identification of unresolved issues.

The conversion of coal to gaseous fuels results in the generation of large quantities of solid waste that must be used beneficially or disposed of in an environmentally acceptable manner. Commercial-scale coal conversion facilities are uncommon in the United States; thus, practical experience with, and research on, coal conversion solid wastes has been limited (10). Fundamental environmental questions about these wastes are related to elemental partitioning in gasification systems and to the mobility of components in gasification solid wastes when contacted by aqueous solutions during disposal. Differences in feed coal and process conditions affect the composition and leachability of these wastes (11). Therefore, proper disposal can not be dictated by the nature of the conversion process alone or the feedstock alone. Coal conversion solid wastes that are demonstrably similar, both physically and chemically, to well-characterized combustion wastes will probably be handled in the same manner as combustion wastes (12).

Data from the source testing and evaluation studies for the solid waste by-products include the following: elemental composition of components, radioactive speciation, organic analysis, evaluation of leaching potential, health and ecology-based bioassays, and a limited array of physical properties related to handling and disposal characteristics. These data are evaluated in this report for general trends in behavior and possible correlations with processes. Although composition and leaching potentials differ for the conversion processes, general trends will be useful in determination of disposal and monitoring requirements.

The remainder of this report is divided into several parts. Section 1 is an introduction. Section 2 summarizes conclusions reached from evaluation of compiled data. Section 3 presents process descriptions. In Section 4, data summaries are given with a discussion of results. References are listed separately. The appendices include Appendix A: Gasifier Flow Rate Data, Appendix B: Internal Quality Control, Appendix C: Data Compilation for Gasifier Ashes, Appendix D: Data Compilation for Cyclone Dusts, and Appendix E: Data Compilation for Gasifier Tars.

SECTION 2

CONCLUSIONS

The major solid waste streams from gasification processes include coarse ash or slag and cyclone dust. The major solid process streams likely to be discharged are by-product tar and oil.

The gasifier ash and cyclone dust originate primarily from the inorganic components in the coal. Data have demonstrated that these materials are non-hazardous under the criteria and test procedures of the Resource Conservation and Recovery Act (RCRA) regulations. However, the physical characteristics and the composition of the waste can vary widely as a function of process configuration, operation, coal feed composition, and coal handling. In addition, these solids do not exhibit a hazardous biological response in bioassay tests.

When values for elemental concentrations in ashes from this series of source testing are generally compared to elemental compositions found in other gasifier ashes, ranges of elements in the waste residues are generally similar (12,13). Available physical properties data, such as densities and particle size distributions, for gasifier ashes are closer to conventional combustion bottom ash than fly ash properties. Other studies have shown that slags produced from gasification and conventional combustion are also similar (13). These results suggest that gasifier slags may not require solid waste management practices substantially different from those currently used for coal combustion solid wastes (10,12) solely based on the elemental compositional data for the slags. Until unresolved issues are better defined, testing should occur on a case by case basis.

Elemental concentration ranges in cyclone dusts from these source tests are comparable to ranges found in other gasifier wastes analyzed in other studies (8). The cyclone dust is also similar in composition to the gasifier ash. Elements enriched in the cyclone dusts included lead, tin, zinc, antimony, and arsenic for most of the EPA Source Testing of gasifiers.

The cyclone dust, the finest fraction of the gasifier solid waste, resembles conventional fly ash (9). These wastes have also been shown to be morphologically similar based on scanning electron micrographs (9). This similarity extends to major oxide constituents: SiO_2, Al_2O_3, and CaO. Proximate/ultimate analyses of cyclone dusts generally had high heating values (as high as >10,900 Btu/lb), indicating that recycle as a fuel may be a viable alternative to disposal. Alternatively, since they have high heating values, they might be used as fuels.

Polynuclear aromatic compounds (PNAs) contribute greatly to possible environmental problems of discharge streams containing tar and oil. These streams include heavy tar solid wastes and gaseous discharges from areas where tar makes up a large portion of particulate matter discharged. Benzo-(a) pyrene is one of the most potentially hazardous PNAs identified in gasifier tars. Besides containing toxic or carcinogenic organic compounds, tars also contain many trace elements. Therefore, tar and oil streams are potentially hazardous and may require careful disposal. Alternatively, since they have high heating values, they might be used as fuels.

Proximate/ultimate analyses of the gasifier by-product tars indicate high heating values which may encourage use of these wastes as a combustion fuel rather than codisposal with other solid wastes. However, metals could be an environmental concern with incineration due to concentration enhancement in the final residue. High carbon and volatiles may indicate a possibility of a hazardous waste classification according to the ignitability characteristic.

Engineering properties of gasifier slag, cyclone dusts, tars, and oils have not been well defined; however, slag and dust appear similar to conventional coal combustion wastes and are likely to be landfilled using current technology. Tars and oils could be codisposed with solid wastes, although this might affect their RCRA classification. (Under RCRA, tars and oils probably will be evaluated as solid wastes according to RCRA definition.) Obviously, utilization of these streams is preferable to disposal.

Detailed characterization data and leaching data are needed to relate waste properties to process types and process variables. In evaluation of possible environmental problems from leaching of these wastes, the RCRA Extraction Procedure Extracts (EP's) and the ASTM extracts did not exceed the established criteria. Although ash-slags would be classified as "nonhazardous" under currently proposed RCRA criteria, soil attenuation experiments would permit a better assessment of actual impacts to affected ground and surface water systems. Some studies of this type are already underway at Oak Ridge National Laboratory (11). In general, leaching studies of gasifier ashes have shown that both inorganic elements and polynuclear aromatic hydrocarbons in the leachates are relatively low and at this time appear not to be of significant environmental concern (20). The major environmental impact associated with disposal of these wastes may be the sulfate dissolution and potential acidification of groundwater. However, studies of soil attenuation of soluble constituents leached from coal conversion solid wastes have shown that soil properties control the degree of attenuation to a greater extent than the chemical composition of the waste leachates (20).

To better assess disposal constraints, engineering properties and physical properties (e.g., permeability, load bearing capacity, strength, and flow properties) would have to be evaluated. To determine the effects on the environment of these wastes in a given disposal site, bench scale and field studies may be required. These field data, in conjunction with comprehensive characterizations of wastes and their leaching properties, may be used to predict leaching and attenuation behavior of mobile pollutants. Design and operation guidelines for coal gasification waste disposal sites should consider the chemical and physical characteristics of the waste, and their behavior in the environment.

SECTION 3

PROCESS DESCRIPTIONS

INTRODUCTION

This section presents brief descriptions and comparisons of the coal gasification facilities for which data are presented in this report. The following types of gasifiers and facilities are included:

- Chapman low-Btu industrial gasifiers at Kingsport, Tennessee;
- Wellman-Galusha low-Btu gasifiers at the Bureau of Mines Twin Cities Metallurgy Research Center, Fort Snelling, Minnesota, and Glen-Gery Brick Company, York, Pennsylvania;
- Riley Gas Producer low-Btu gasifier at Worcester, Massachusetts;
- Foster-Wheeler/STOIC low-Btu industrial gasifier at the University of Minnesota, Duluth (UMD);
- Lurgi-type medium-Btu commercial gasifiers at Kosovo, Yugoslavia;
- Kellogg-Rust/Westinghouse (KRW) medium-Btu gasifier PDU at Madison, Pennsylvania;
- Koppers-Totzek medium-Btu commercial gasifiers at Modderfontein, South Africa;

- Koppers-Totzek (GKT) medium-Btu commercial gasifier at Ptolemais, Greece; and

- Texaco medium-Btu demonstration gasifier at the Ruhrkohle/Ruhrchemie facility in Oberhausen-Holten, Federal Republic of Germany.

Table 1 presents a summary of the features of the coal handling/preparation, coal feeding, gasification, and downstream processes (including gas cleanup and ash removal/handling) present at each facility. The similarities and differences will be discussed in more detail later; however, some of the salient differences between processes are summarized below:

- Oxygen versus Air-Injection: Gasifiers that use air as their source of oxygen produce a gas having a lower calorific value than those that use pure or nearly pure oxygen. This is due to the nitrogen diluent present in air. Chapman, Wellman-Galusha, Riley, and Foster-Wheeler/STOIC gasifiers are of the so-called "low-Btu" type, while the Koppers-Totzek and Texaco gasifiers both produce "medium-Btu" gas. The Lurgi and KRW gasifiers can be operated in either mode; the data presented here were obtained on systems producing medium-Btu gas.

- Bed Type: There are three principal gasifier bed types: moving-bed, fluidized-bed, and entrained-bed. Moving-bed (sometimes referred to as fixed-bed) gasifiers feature a layer of coal which is generally supported on a grate through which air (or oxygen) and steam are passed. In thin bed systems, less than a 0.5 m layer of coal is maintained on the coal grate. In thick bed systems, bed depths of 2 to 5 m are more typical. The direction of movement of the coal relative to the gas is countercurrent. In fluidized-bed gasifiers the upward velocity of the gas stream is such that the fluid drag forces nearly balance the downward forces due to the weight of the coal/ char particles. The particles act

TABLE 1. COMPARISON OF COAL GASIFICATION FACILITIES

	Chapman	Wellman-Galusha (Fort Snelling)	Wellman-Galusha (Glen-Gery)	Riley	Foster-Wheeler/ STOIC
COAL HANDLING					
Receive presized coal	X	X	X	X	X
Crush/pulverize					
Screen		X			X
Thermal drying					
Slurrying					
Air classifying					
COAL FEEDING					
Lock hoppers		X	X	X	X
Screw feed/entrainment					
Slurry pumping					
Barrel valve	X				
GASIFICATION					
Atmospheric (A)/Pressurized (P)	A	A	A	A	A
Moving- (M)/Fluid- (F)/Entrained-bed (E)	M	M	M	M	M
Thin bed (T)/Deep bed (D)	T	D	D	T	D
Slagging (S)/Agglomerating (A)/ Dry ash (D)	D	D	D	D	D
Single-stage (S)/Two-stage (T)	S	S	S	S	T
Cocurrent (C)/Countercurrent (CC)	CC	CC	CC	CC	CC
Air blown (A)/O_2 blown (O)	A	A	A	A	A
GAS CLEANUP					
Cyclones	X	X	X	X	X
ESP					X
Quench/Scrubbing	X				
Acid gas removal					
ASH REMOVAL/HANDLING					
Lockhoppers					
Ash plow	X			X	X
Slide valve		X	X		
Water quench	X	X	X	X	X
Conveyor/Drag chain	X				X

(continued)

TABLE 1. COMPARISON OF COAL GASIFICATION FACILITIES (Continued)

	Lurgi-type (Kosovo)	KRW PDU	Koppers-Totzek (Modderfontein)	Koppers-Totzek (Ptolemais)	Texaco (Ruhrchemie)
COAL HANDLING					
Receive presized coal					
Crush/pulverize	X	X	X	X	X
Screen	X				
Thermal drying	X	X	X	X	
Slurrying					X
Air classifying		X			
COAL FEEDING					
Lock hoppers	X	X			
Screw feed/entrainment			X	X	
Slurry pumping					X
Barrel valve					
GASIFICATION					
Atmospheric (A)/Pressurized (P)	P	P	A	A	P
Moving- (M)/Fluid- (F)/Entrained-bed (E)	M	F	E	E	E
Thin bed (T)/Deep bed (D)	D	D	–[a]	–[a]	–[a]
Slagging (S)/Agglomerating (A)/Dry ash (D)	D	A	S	S	S
Single-stage (S)/Two-stage (T)	S	S	S	S	S
Cocurrent (C)/Countercurrent (CC)	CC	CC	C	C	C
Air blown (A)/O_2 blown (O)	O	O	O	O	O
GAS CLEANUP					
Cyclones		X			
ESP			X	X	
Quench/Scrubbing	X	X	X	X	X
Acid gas removal	X		X	X	X
ASH REMOVAL/HANDLING					
Lockhoppers	X	X			X
Ash plow					
Slide valve					
Water quench	X		X	X	X
Conveyor/Drag chain	X		X	X	X

[a] Not applicable.

as if they were a turbulent fluid. In entrained-bed gasifiers, the coal and gases move in the same direction (co-current). Of the gasifiers represented here, only the KRW is a fluidized-bed gasifier; entrained-bed gasifiers include the Koppers-Totzek and Texaco gasifiers. All the rest are of the fixed-bed type.

- Single-stage versus Two-stage: In single-stage gasifiers, the raw product gas is taken off at a single location. In two-stage gasifiers, two separate raw product gas streams are generated. In a fixed-bed, two-stage design the upper gas product is richer in heavier hydrocarbon gases and aerosols formed by the release of coal volatile matter and water vapor resulting from the release of moisture in the feed coal. The lower gas product is richer in lighter combustible gases such as carbon monoxide and hydrogen. The only two-stage gasifier presented here is the Foster-Wheeler/STOIC gasifier.

- Atmosphere Pressure versus Elevated Pressure: Operation at elevated pressure allows the use of smaller vessels for equivalent gas production. Increased partial pressures of reactive gases may increase reaction rates and/or alter reaction equilibria in both the gasifier and in downstream units. Additional effects of pressurized operation include:

--reduced needs for compression of raw gas prior to downstream treatment units (e.g., physical absorption type acid gas removal processes) or prior to injection into a pipeline transmission system.

--generation of flash gases from depressurization of by-product liquids, resulting in an additional waste gas stream.

Of the gasifiers considered here, only three were operated at elevated pressure; the Lurgi-type (Kosovo), KRW, and Texaco (Ruhrkohle/Ruhrchemie) gasifiers. The rest were operated at or near atmospheric pressure.

The remainder of this process description section consists of two subsections: the first discusses and compares the gasification processes (including coal preparation and coal feeding), while the second deals with downstream processing operations.

SUMMARY AND COMPARISON OF GASIFICATION OPERATIONS

Coal gasification involves the conversion of coal to gaseous species which can be burned as fuels or which can be used as feedstocks in the formation of fuels or other products. There are several general types of phenomena which occur during coal gasification which are common to all processes. These include coal drying and devolatilization, gasification, oxidation (or combustion), water-gas shift, volatilization and reaction of coal sulfur and nitrogen, and production of unreacted residuals (ash). Each of these may occur in different areas of the gasification reactor depending on the method used to contact the coal and the reactant gases.

Drying and Devolatilization

As the coal is heated, moisture is given off and the volatile fraction undergoes pyrolysis (i.e., thermal decomposition). The composition of the volatiles (some of which may be liquids or even solids at ambient conditions) depends on a number of factors including coal rank, coal particle thermal history (e.g., heating rate, duration of heating, and final temperature reached), and the composition and pressure of the reactant gas. Anthracite, for example, gives off relatively little volatile matter compared with bituminous coal or lignite. If devolatilization occurs at relatively low temperatures, the volatile fraction contains appreciable amounts of tar and oil aerosols. If devolatilization occurs at higher temperatures, these tars and oils are largely converted, by further pyrolysis into lighter hydrocarbons, methane, hydrogen, carbon monoxide, and carbon dioxide.

Gasification

In the gasification zone, various reactions occur between the carbon in the coal and the hot gases present in the oxidation zone. The principal gasification reactions of interest are:

$$C + CO_2 + \text{heat} \text{ --------> } 2CO$$

$$C + H_2O + \text{heat} \text{ --------> } CO + H_2$$

$$C + 2H_2 \text{ --------> } CH_4 + \text{heat}$$

As can be seen, the primary products of gasification are carbon monoxide, hydrogen, and methane. The energy required by the first two reactions is furnished by the sensible heat of the gases leaving the oxidation zone. The extent to which these competing reactions proceed to completion depends on factors such as pressure, temperature, residence time, and reactant concentrations.

Oxidation (Combustion)

Oxidation involves the heterogeneous reaction between coal carbon and oxygen to produce CO and CO_2:

$$C + O_2 \text{ --------> } CO_2 + \text{heat}$$

$$C + 1/2\ O_2 \text{ --------> } CO + \text{heat}$$

These reactions result in the release of energy that allows the gasification reactions to proceed. The ratio of carbon monoxide to carbon dioxide formed in the oxidation zone depends on the oxygen partial pressure and the temperature. If excess oxygen is present, some of the carbon monoxide will be converted to CO_2 by gas phase oxidation.

In addition, in entrained-bed gasifiers and some fluidized-bed gasifiers where devolatilization occurs in an oxygen-rich environment, tars and oils and other organics are also oxidized in the gas phase, forming carbon monoxide, carbon dioxide, and hydrogen.

Water-Gas Shift

An important gas-phase reaction occurring in the gasifier involves the equilibrium among carbon monoxide, carbon dioxide, hydrogen, and water vapor:

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

The composition of the raw product leaving the gasifier is significantly influenced by this equilibrium. High temperature favors the formation of carbon monoxide and water vapor. The relative partial pressures of the various reactants also influence the equilibrium composition.

Sulfur and Nitrogen Reactions

Coal contains varying amounts of sulfur and nitrogen. Significant reaction products formed from these elements during gasification include ammonia, hydrogen cyanide, hydrogen sulfide, carbonyl sulfide, and other organic sulfur species (such as mercaptans). The quantities of such species formed depend on a number of factors including coal sulfur and nitrogen content, temperature, pressure, and hydrogen concentration in the gas. The ratio of carbonyl sulfide to hydrogen sulfide is a particularly important concern because this ratio can affect the selection, design, and performance of downstream acid gas removal and sulfur recovery processes. As with the water-gas shift reactions discussed above, the ratio of COS to H_2S in the raw gas is affected by the steam and carbon dioxide content of the gas due to the chemical equilibrium which is maintained at high temperatures among these four species:

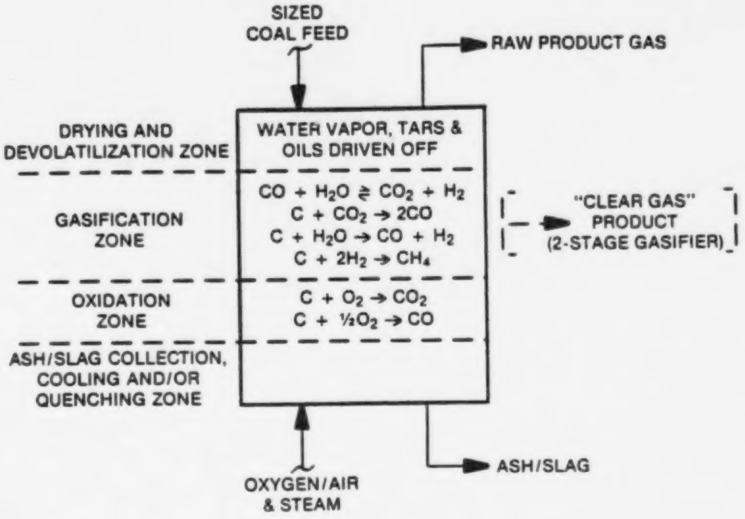
$$H_2S + CO_2 \rightleftharpoons COS + H_2O$$

Similar relationships may also hold for nitrogen species such as ammonia and hydrogen cyanide.

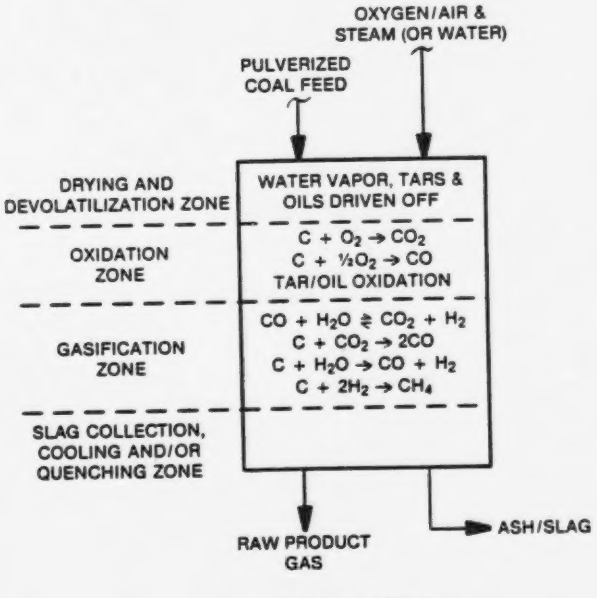
Solid Waste

Coal contains substantial quantities of nonreactive mineral matter which remains after the coal has been gasified. The resulting solid waste will be in the form of ash or solidified slag droplets, depending primarily on the reactor operating temperature and the ash fusion point. Fixed-bed gasifiers can be operated to produce either a "dry", unfused ash (low-temperature operation) or a fused slag by-product (high-temperature operation). Entrained-bed gasifiers operate at high temperatures and produce a slag by-product. Some fluidized-bed gasifiers operate at a temperature at which the ash particles are soft and sticky and form agglomerates that are removed from the gasifier. Some of the mineral matter components may also be volatilized; the extent to which this occurs depends on the temperature and the chemical forms in which these compounds are found in the coal.

The susceptibility to leaching of the species remaining in the ash or slag is also likely to vary depending on their solubility and the ease with which water can penetrate the solid. For example, fused slags are less subject to leaching than more porous ash particles.

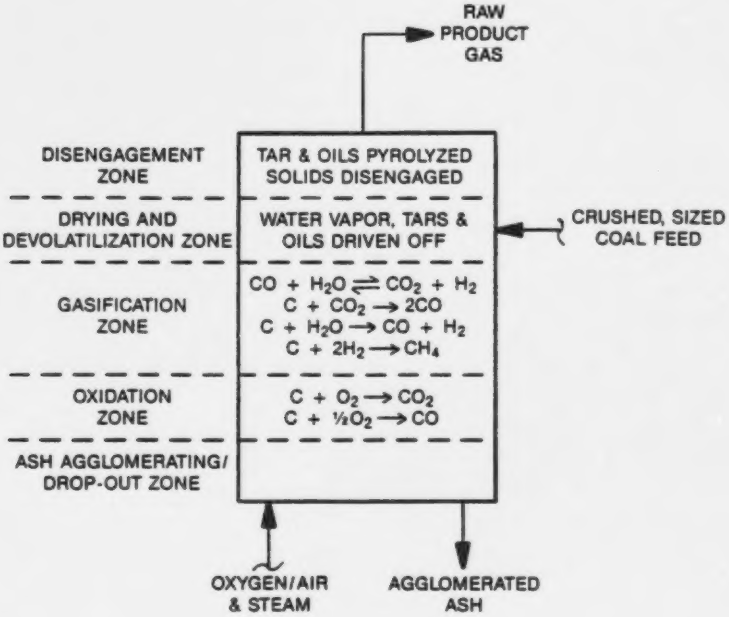

SIZED COAL FEED
RAW PRODUCT GAS
DRYING AND DEVOLATILIZATION ZONE
WATER VAPOR, TARS & OILS DRIVEN OFF
GASIFICATION ZONE
$CO + H_2O \rightleftharpoons CO_2 + H_2$
$C + CO_2 \rightarrow 2CO$
$C + H_2O \rightarrow CO + H_2$
$C + 2H_2 \rightarrow CH_4$
"CLEAR GAS" PRODUCT (2-STAGE GASIFIER)
OXIDATION ZONE
$C + O_2 \rightarrow CO_2$
$C + \frac{1}{2}O_2 \rightarrow CO$
ASH/SLAG COLLECTION, COOLING AND/OR QUENCHING ZONE
OXYGEN/AIR & STEAM
ASH/SLAG

FIXED BED,
COUNTERCURRENT GASIFIER


OXYGEN/AIR & STEAM (OR WATER)
PULVERIZED COAL FEED
DRYING AND DEVOLATILIZATION ZONE
WATER VAPOR, TARS & OILS DRIVEN OFF
OXIDATION ZONE
$C + O_2 \rightarrow CO_2$
$C + \frac{1}{2}O_2 \rightarrow CO$
TAR/OIL OXIDATION
GASIFICATION ZONE
$CO + H_2O \rightleftharpoons CO_2 + H_2$
$C + CO_2 \rightarrow 2CO$
$C + H_2O \rightarrow CO + H_2$
$C + 2H_2 \rightarrow CH_4$
SLAG COLLECTION, COOLING AND/OR QUENCHING ZONE
RAW PRODUCT GAS
ASH/SLAG

ENTRAINED-BED,
CO-CURRENT GASIFIER

Figure 1. Conceptual configurations of different gasifier bed types.


RAW PRODUCT GAS
DISENGAGEMENT ZONE
TAR & OILS PYROLYZED SOLIDS DISENGAGED
DRYING AND DEVOLATILIZATION ZONE
WATER VAPOR, TARS & OILS DRIVEN OFF
CRUSHED, SIZED COAL FEED
GASIFICATION ZONE
CO + H2O ⇌ CO2 + H2
C + CO2 → 2CO
C + H2O → CO + H2
C + 2H2 → CH4
OXIDATION ZONE
C + O2 → CO2
C + ½O2 → CO
ASH AGGLOMERATING/ DROP-OUT ZONE
OXYGEN/AIR & STEAM
AGGLOMERATED ASH

FLUIDIZED BED

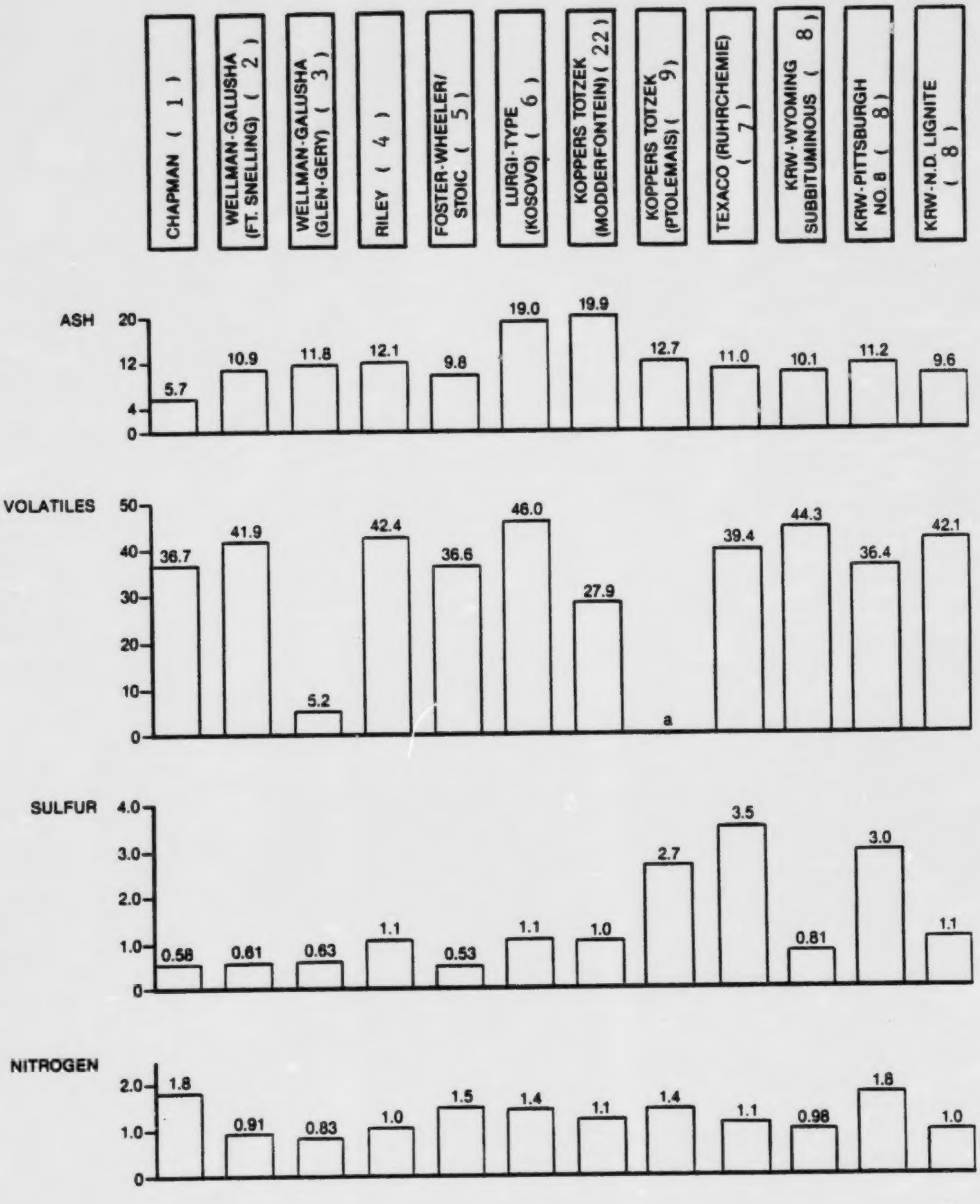
Figure 1. (Continued)

Figure 1 shows the conceptual zones into which fixed-bed, fluidized-bed, and entrained-bed gasifiers may be divided. Note that in the fixed-bed and fluidized-bed gasifiers, the relative direction of gas and solid flows is countercurrent, while it is co-current in the entrained-bed gasifier. Also note the differences in the order of the various reaction zones.

Associated closely with the gasification operation are the equipment and operations required to prepare the coal and feed it into the gasifier vessels. In the case of most small, low-Btu gasification facilities, very limited coal preparation is performed. These facilities typically gasify coal which has been sized prior to its delivery to the site. Some screening of the coal for removal of fines is performed at two of the low-Btu facilities tested (Wellman-Galusha at Fort Snelling, and Foster-Wheeler/STOIC at UMD). As-received coal is crushed and sized on site at all of the medium-Btu facilities considered in this report. At the Lurgi-type (Kosovo), KRW PDU, and Koppers-Totzek (Modderfontein and Ptolemais) facilities, coal drying is performed. The entrained-bed gasifiers (Koppers-Totzek and Texaco) require more extensive preparation (crushing and pulverizing) to produce the finely divided coal feed used in these gasifiers.

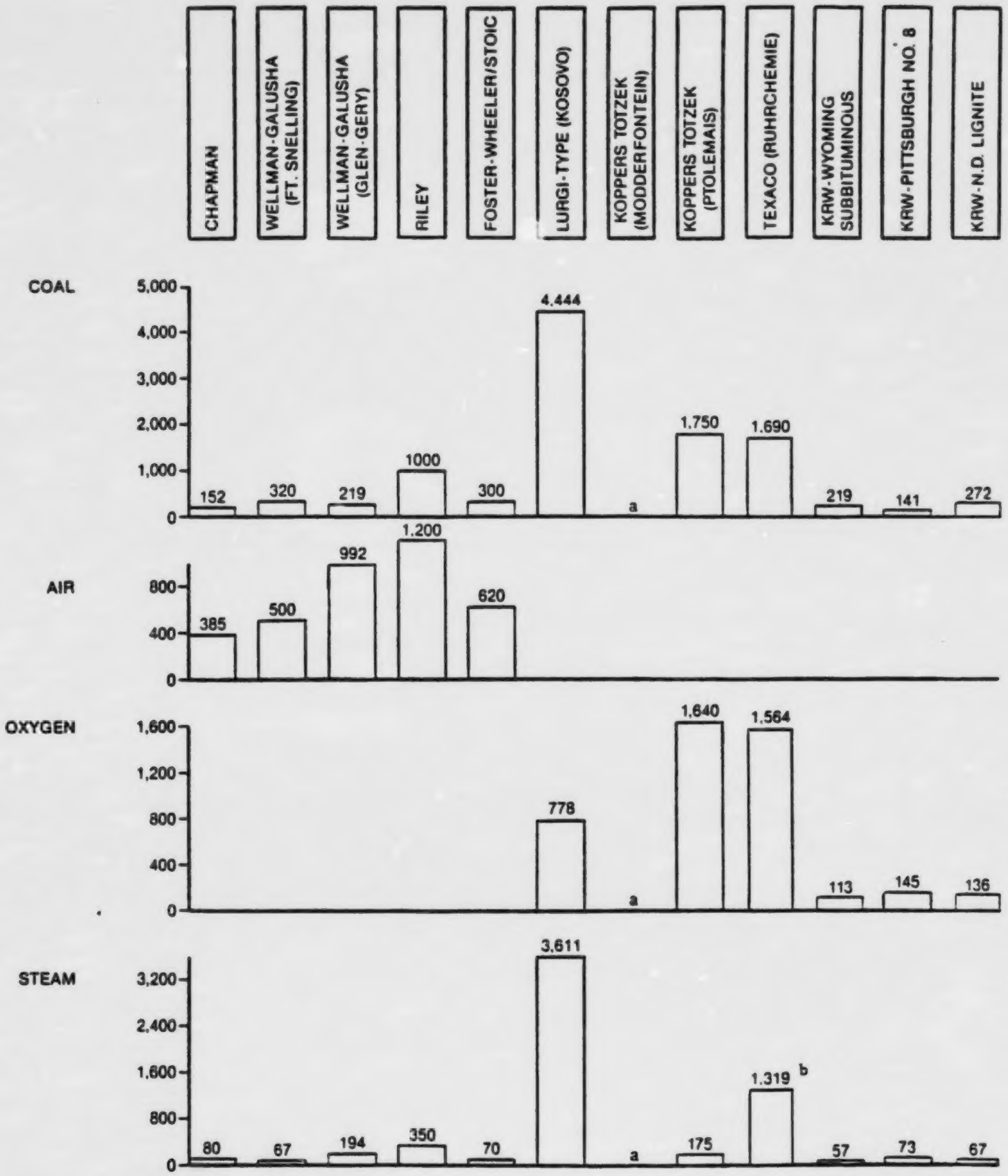
A variety of methods are used to feed the prepared coal into the gasifiers. Lockhoppers are used with Wellman-Galusha, Riley, Foster-Wheeler/STOIC, Lurgi and KRW gasifiers. At the Chapman gasifier facility, coal is fed by means of a rotary feeding device known as a barrel valve. In the GKT gasifier, coal is augered out of a storage vessel and transported to the gasifier in a heated stream of steam and oxygen using a screw conveyor. The Texaco gasifier utilizes a slurry system in which pulverized coal is mixed with water, preheated, and pumped into the gasifier vessel.

Figures 2 through 4 summarize coal composition, gasifier feed rates, and reactant ratios for each of the gasification facilities. Flow rates are shown on a "per gasifier" basis to facilitate comparisons. The reactant ratios were calculated based on the reported feed rates. For the air-blown



[a] No Data.

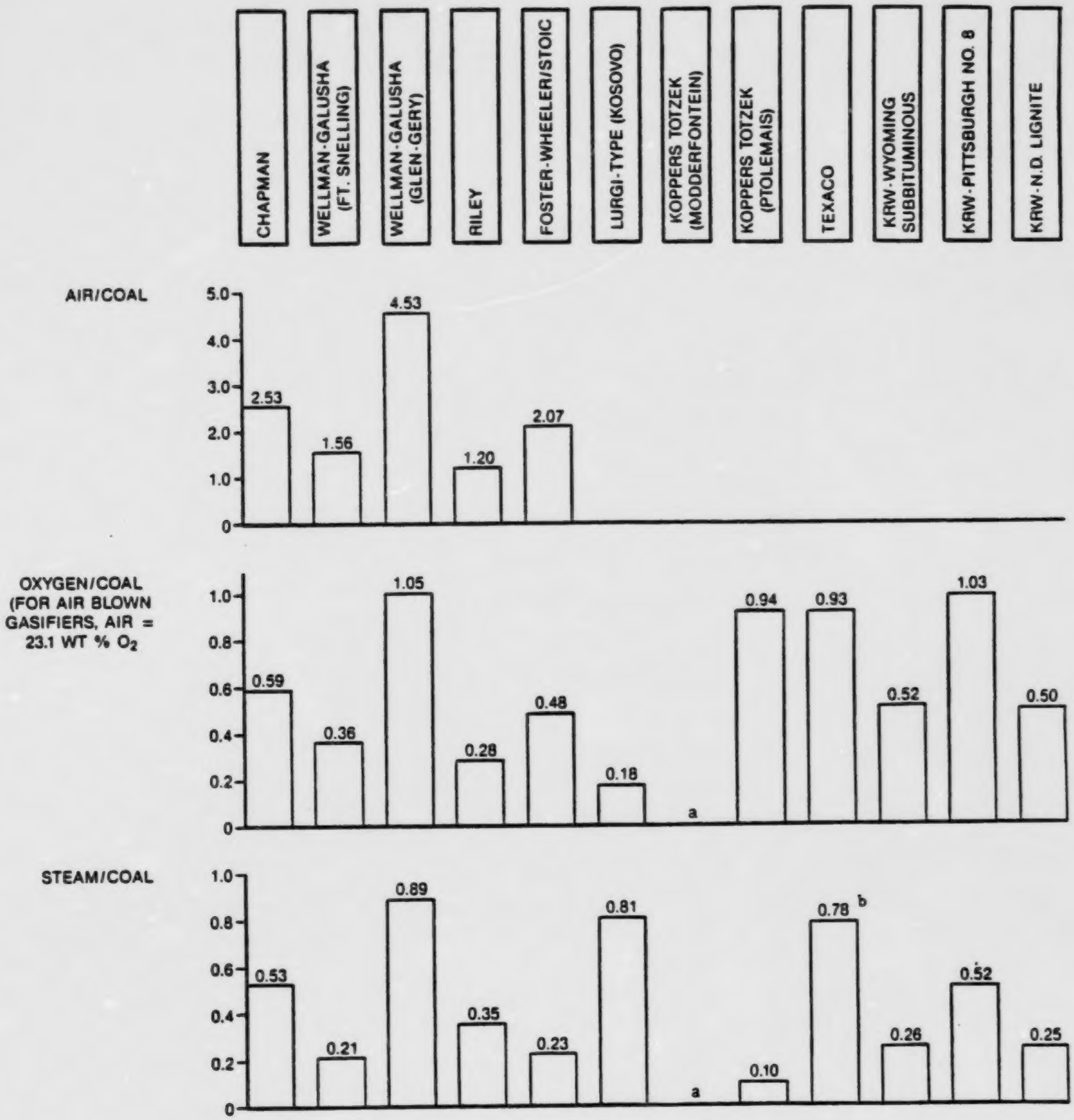
Figure 2. Comparative coal feedstock analyses, dry basis, wt %.



[a] No data available.

[b] For the Texaco Gasifier Only, the Steam Flow Rate is Taken as the Fresh Makeup Slurry Water, Coal Moisture, and Water in Additive and Flocculant.

Figure 3. Comparative gasifier feed rates, g/sec-gasifier.



[a] No data available.

[b] For the Texaco Gasifier Only, the Steam Flow Rate is Taken as the Fresh Makeup Slurry Water, Coal Moisture, and Water in Additive and Flocculant.

Figure 4. Comparative gasifier feed ratios, kg/kg.

gasifiers, the oxygen to coal ratio was calculated based on an oxygen content of 23.1 percent by weight for air.

SUMMARY AND COMPARISON OF DOWNSTREAM PROCESSING OPERATIONS

Processing operations downstream of gasification are needed to perform various functions including:

- Removal of entrained particulates (fly ash, tar, oil, etc.),
- Removal of gaseous contaminants (primarily sulfur and nitrogen species),
- Cooling of the raw product gas,
- Handling and disposal of solid wastes,
- Treatment and disposal of wastewater,
- Recovery of by-products (e.g., sulfur, ammonia, organics),
- Control of air pollutants, and
- Upgrading of the raw gas.

All of these processing operations are not present in all gasification facilities. Those found in the gasification facilities included in this report were shown in Table 1. Figures 5 through 14 are simplified block flow diagrams of these facilities. The major processing units and streams present in each of the facilities are shown, together with stream temperature data obtained at the time the facilities were characterized. Those streams for which composition and/or flow rate data were obtained are also

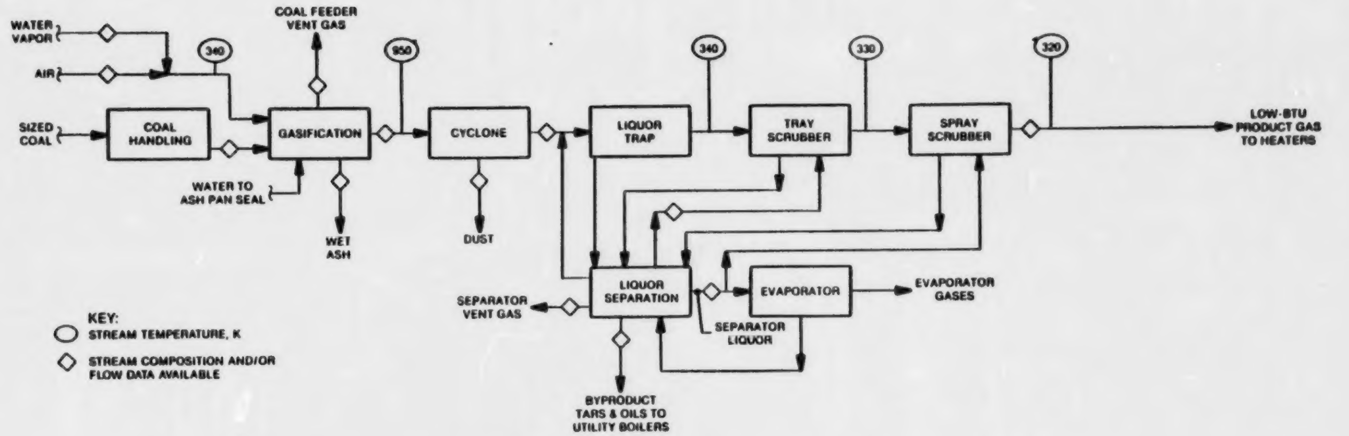

WATER VAPOR
AIR
SIZED COAL
COAL HANDLING
340
COAL FEEDER VENT GAS
GASIFICATION
WATER TO ASH PAN SEAL
WET ASH
950
CYCLONE
DUST
LIQUOR TRAP
340
TRAY SCRUBBER
330
SPRAY SCRUBBER
320
LOW-BTU PRODUCT GAS TO HEATERS
LIQUOR SEPARATION
SEPARATOR VENT GAS
EVAPORATOR
EVAPORATOR GASES
SEPARATOR LIQUOR
BYPRODUCT TARS & OILS TO UTILITY BOILERS
KEY:
STREAM TEMPERATURE, K
STREAM COMPOSITION AND/OR FLOW DATA AVAILABLE

Figure 5. Simplified block flow diagram of Chapman gasifier.

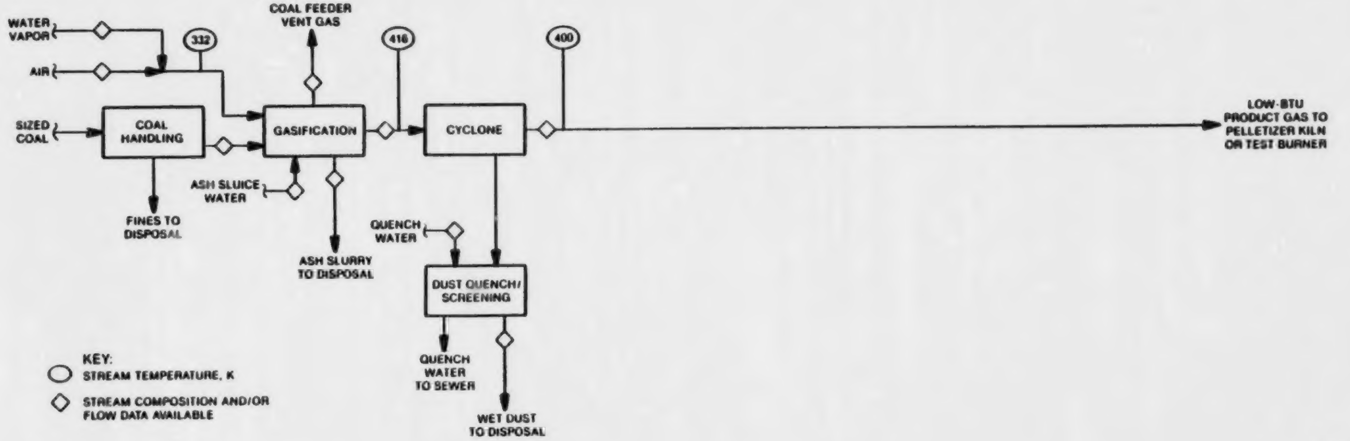

WATER VAPOR
AIR
SIZED COAL
COAL HANDLING
FINES TO DISPOSAL
332
COAL FEEDER VENT GAS
GASIFICATION
ASH SLUICE WATER
ASH SLURRY TO DISPOSAL
416
CYCLONE
400
LOW-BTU PRODUCT GAS TO PELLETIZER KILN OR TEST BURNER
QUENCH WATER
DUST QUENCH/ SCREENING
QUENCH WATER TO SEWER
WET DUST TO DISPOSAL
KEY:
STREAM TEMPERATURE, K
STREAM COMPOSITION AND/OR FLOW DATA AVAILABLE

Figure 6. Simplified block flow diagram of Wellman-Galusha (Ft. Snelling) gasifier.

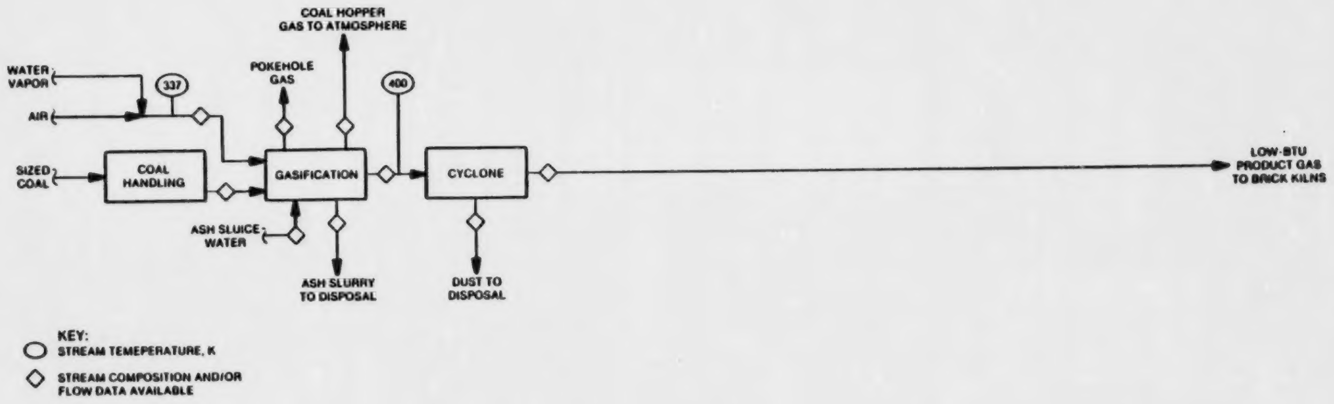

COAL HOPPER GAS TO ATMOSPHERE
WATER VAPOR
337
POKEHOLE GAS
400
AIR
SIZED COAL
COAL HANDLING
GASIFICATION
CYCLONE
LOW-BTU PRODUCT GAS TO BRICK KILNS
ASH SLUICE WATER
ASH SLURRY TO DISPOSAL
DUST TO DISPOSAL
KEY:
STREAM TEMEPERATURE, K
STREAM COMPOSITION AND/OR FLOW DATA AVAILABLE

Figure 7. Simplified block flow diagram of Wellman-Galusha (Glen-Gery) gasifier.

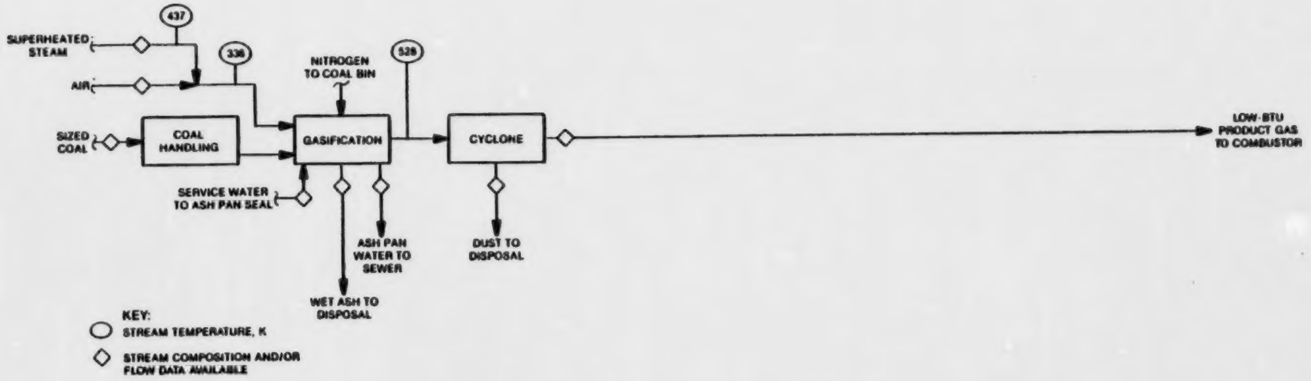

437
SUPERHEATED STEAM
336
NITROGEN TO COAL BIN
528
AIR
SIZED COAL
COAL HANDLING
GASIFICATION
CYCLONE
LOW-BTU PRODUCT GAS TO COMBUSTOR
SERVICE WATER TO ASH PAN SEAL
ASH PAN WATER TO SEWER
DUST TO DISPOSAL
WET ASH TO DISPOSAL
KEY:
STREAM TEMPERATURE, K
STREAM COMPOSITION AND/OR FLOW DATA AVAILABLE

Figure 8. Simplified block flow diagram of Riley gasifier.

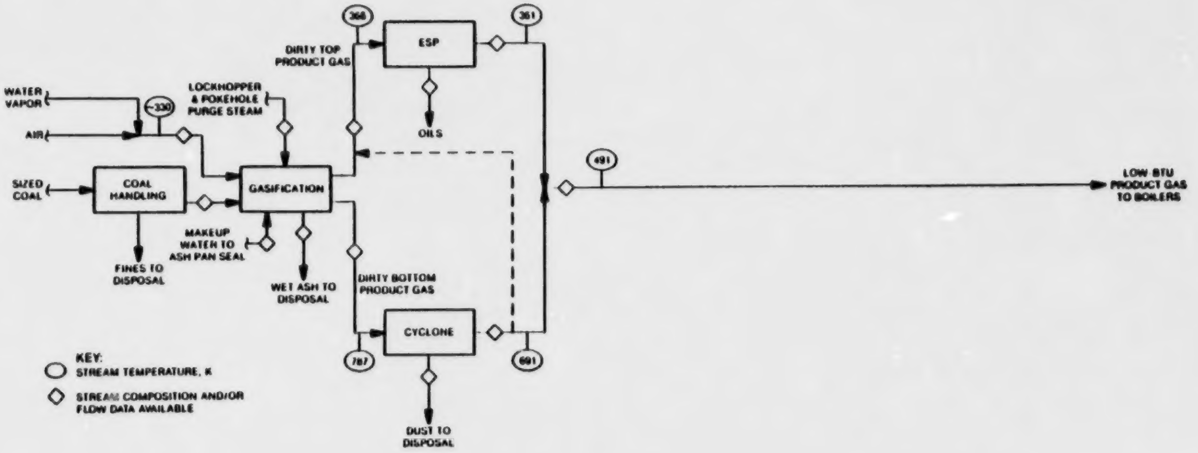

WATER VAPOR
AIR
SIZED COAL
COAL HANDLING
FINES TO DISPOSAL
~330
LOCKHOPPER & POKEHOLE PURGE STEAM
GASIFICATION
MAKEUP WATER TO ASH PAN SEAL
WET ASH TO DISPOSAL
DIRTY TOP PRODUCT GAS
368
ESP
OILS
361
DIRTY BOTTOM PRODUCT GAS
787
CYCLONE
DUST TO DISPOSAL
691
491
LOW BTU PRODUCT GAS TO BOILERS
KEY:
STREAM TEMPERATURE, K
STREAM COMPOSITION AND/OR FLOW DATA AVAILABLE

Figure 9. Simplified block flow diagram of Foster-Wheeler/STOIC gasifier.

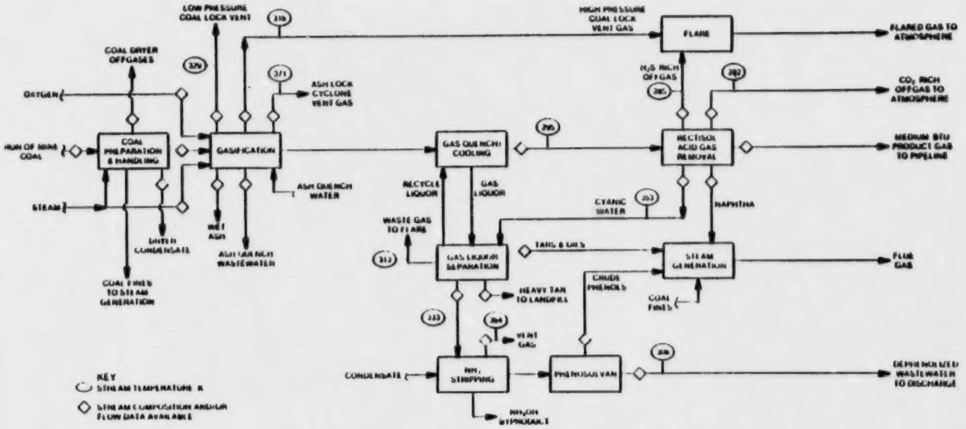

OXYGEN
RUN OF MINE COAL
STEAM
COAL DRYER OFFGASES
COAL PREPARATION & HANDLING
DRYER CONDENSATE
COAL FINES TO STEAM GENERATION
LOW PRESSURE COAL LOCK VENT
GASIFICATION
ASH LOCK CYCLONE VENT GAS
ASH QUENCH WATER
WET ASH
ASH QUENCH WASTEWATER
HIGH PRESSURE COAL LOCK VENT GAS
FLARE
FLARED GAS TO ATMOSPHERE
GAS QUENCH COOLING
RECYCLE LIQUOR
GAS LIQUOR
WASTE GAS TO FLARE
GAS LIQUOR SEPARATION
HEAVY TAR TO LANDFILL
TARS & OILS
CYANIC WATER
H₂S RICH OFFGAS
RECTISOL ACID GAS REMOVAL
CO₂ RICH OFFGAS TO ATMOSPHERE
MEDIUM BTU PRODUCT GAS TO PIPELINE
NAPHTHA
STEAM GENERATION
FLUE GAS
CRUDE PHENOLS
COAL FINES
CONDENSATE
NH₃ STRIPPING
VENT GAS
NH₄OH BYPRODUCT
PHENOSOLVAN
DEPHENOLIZED WASTEWATER TO DISCHARGE
KEY
STREAM TEMPERATURE, K
STREAM COMPOSITION AND/OR FLOW DATA AVAILABLE

Figure 10. Simplified block flow diagram of Lurgi-type gasifier.

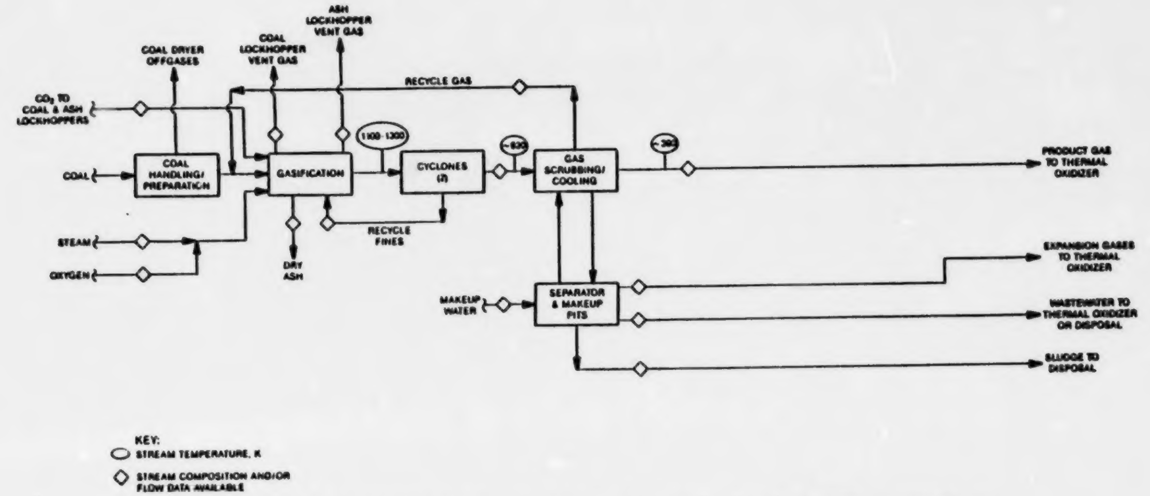

COAL DRYER OFFGASES
COAL LOCKHOPPER VENT GAS
ASH LOCKHOPPER VENT GAS
RECYCLE GAS
CO_2 TO COAL & ASH LOCKHOPPERS
COAL
COAL HANDLING/ PREPARATION
GASIFICATION
1100-1300
CYCLONES (2)
~830
GAS SCRUBBING/ COOLING
~380
PRODUCT GAS TO THERMAL OXIDIZER
STEAM
OXYGEN
DRY ASH
RECYCLE FINES
EXPANSION GASES TO THERMAL OXIDIZER
MAKEUP WATER
SEPARATOR & MAKEUP PITS
WASTEWATER TO THERMAL OXIDIZER OR DISPOSAL
SLUDGE TO DISPOSAL
KEY:
STREAM TEMPERATURE, K
STREAM COMPOSITION AND/OR FLOW DATA AVAILABLE

Figure 11. Simplified block flow diagram of KRW PDU gasifier.

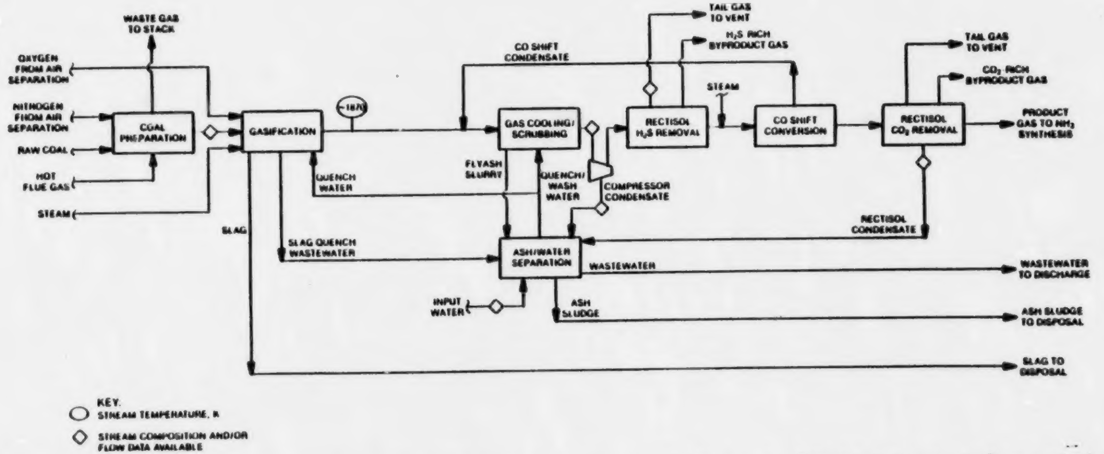

WASTE GAS TO STACK
OXYGEN FROM AIR SEPARATION
NITROGEN FROM AIR SEPARATION
RAW COAL
HOT FLUE GAS
STEAM
COAL PREPARATION
GASIFICATION
~1870
SLAG
QUENCH WATER
SLAG QUENCH WASTEWATER
CO SHIFT CONDENSATE
GAS COOLING/ SCRUBBING
FLYASH SLURRY
QUENCH/ WASH WATER
COMPRESSOR CONDENSATE
TAIL GAS TO VENT
H_2S RICH BYPRODUCT GAS
RECTISOL H_2S REMOVAL
STEAM
CO SHIFT CONVERSION
TAIL GAS TO VENT
CO_2 RICH BYPRODUCT GAS
RECTISOL CO_2 REMOVAL
PRODUCT GAS TO NH_3 SYNTHESIS
RECTISOL CONDENSATE
ASH/WATER SEPARATION
WASTEWATER
WASTEWATER TO DISCHARGE
INPUT WATER
ASH SLUDGE
ASH SLUDGE TO DISPOSAL
SLAG TO DISPOSAL
KEY:
STREAM TEMPERATURE, K
STREAM COMPOSITION AND/OR FLOW DATA AVAILABLE

Figure 12. Simplified block flow diagram of Koppers-Totzek (Modderfontein) gasifier.

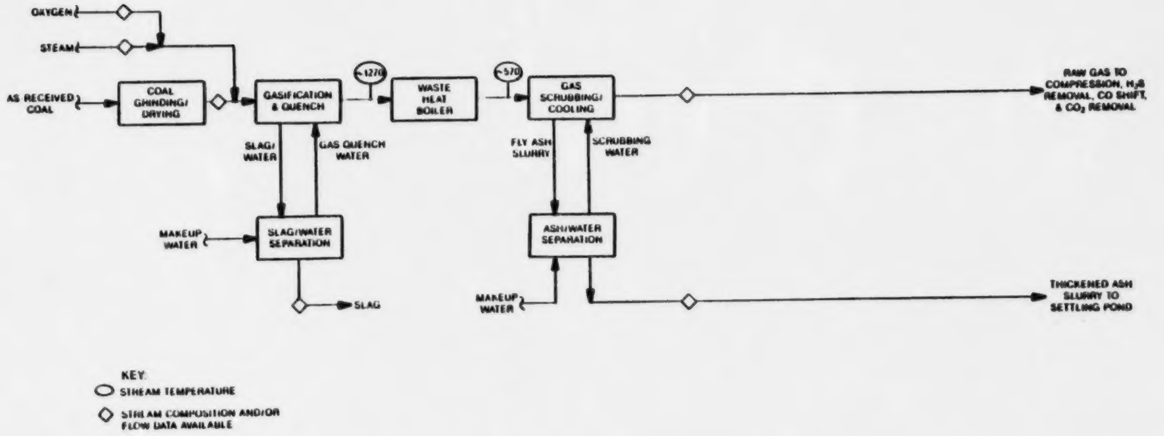

OXYGEN
STEAM
AS RECEIVED COAL
COAL GRINDING/ DRYING
GASIFICATION & QUENCH
~1270
WASTE HEAT BOILER
~570
GAS SCRUBBING/ COOLING
RAW GAS TO COMPRESSION, H2S REMOVAL, CO SHIFT, & CO2 REMOVAL
SLAG/ WATER
GAS QUENCH WATER
FLY ASH SLURRY
SCRUBBING WATER
MAKEUP WATER
SLAG/WATER SEPARATION
ASH/WATER SEPARATION
SLAG
MAKEUP WATER
THICKENED ASH SLURRY TO SETTLING POND
KEY
STREAM TEMPERATURE
STREAM COMPOSITION AND/OR FLOW DATA AVAILABLE

Figure 13. Simplified block flow diagram of Koppers-Totzek (Ptolemais) gasifier.

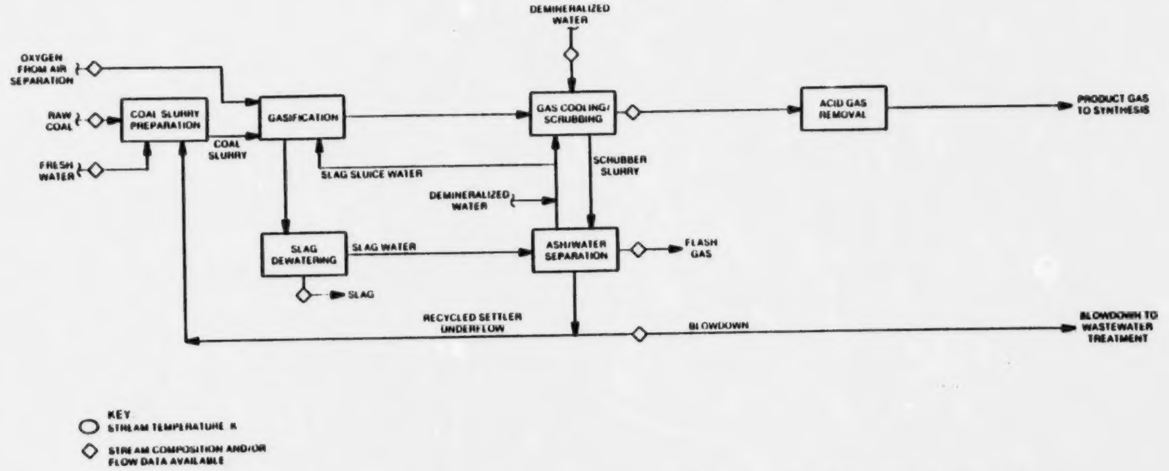

DEMINERALIZED WATER
OXYGEN FROM AIR SEPARATION
RAW COAL
FRESH WATER
COAL SLURRY PREPARATION
COAL SLURRY
GASIFICATION
GAS COOLING/ SCRUBBING
ACID GAS REMOVAL
PRODUCT GAS TO SYNTHESIS
SLAG SLUICE WATER
SCRUBBER SLURRY
DEMINERALIZED WATER
SLAG DEWATERING
SLAG WATER
ASH/WATER SEPARATION
FLASH GAS
SLAG
RECYCLED SETTLER UNDERFLOW
BLOWDOWN
BLOWDOWN TO WASTEWATER TREATMENT
KEY
STREAM TEMPERATURE K
STREAM COMPOSITION AND/OR FLOW DATA AVAILABLE

Figure 14. Simplified block flow diagram of Texaco/Ruhrchemie gasifier.

indicated. These diagrams clearly show similarities and differences among the facilities.

In general, the low-Btu gasification facilities have much less extensive downstream processing than the larger, more complex medium-Btu facilities. In addition, since the emphasis at the KRW PDU is on gasifier development, limited gas cleaning is practical. In several of the low-Btu facilities, gas cleanup consists only of removing entrained particulates, typically by the use of cyclone separators. This is particularly true of the facilities which produce a hot fuel gas for direct combustion in a process furnace. The Foster-Wheeler/STOIC facility (which features two-stage gasification) utilizes an electrostatic precipitator (ESP) to remove oil and tar particulates from the top gas and a cyclone to remove dust from the bottom gas. Of the low-Btu gasifiers tested, only the Chapman facility utilizes wet scrubbing and produces a cooled fuel gas, by-product tars and oils, and a process condensate (wastewater) stream. Some type of wet scrubbing is used in all of the medium-Btu facilities. None of the low-Btu facilities have acid gas removal systems; all of the commercial medium-Btu facilities have such units.

Ash/slag removal techniques also vary. All of the facilities except the KRW PDU use water to quench the hot ash/slag or to facilitate its removal from the gasifier vessel by sluicing. The pressurized gasifiers (Lurgi, KRW, and Texaco) all utilize lock hoppers to remove ash/slag. The others utilize ash plows, mechanical conveyors, or slide valves.

The downstream processing operations can significantly influence the fates of the various solid, liquid, and gaseous pollutants generated in the gasifier. Components originally found in the raw gas may be removed by these operations and distributed into a number of secondary solid, liquid, or gaseous streams. This distribution depends on the way in which these processes are linked together, how they are designed and operated, and on stream compositions.

Flow rate data for the major streams entering and leaving the downstream processing units for each of the facilities considered are summarized in Appendix A.

SECTION 4

SUMMARY OF DATA

This section presents an overview of collected data which characterize gasifier ashes, cyclone dusts, and tars. Gasifier ash (slag) data are presented in the first subsection, all cyclone dust data are presented in the second, and tar and oil data are addressed in the third subsection. Within each of these subsections, data are ordered according to chemical properties, physical characteristics, and evaluation of potential environmental problems. Table 2 illustrates a summary of data categories. Actual data are given in the appendices.

In reviewing data from EPA Source Test and Evaluation Studies, several important issues must be considered. The major objective of these studies was to provide survey data under normal operating conditions from which a preliminary assessment of potential environmental impacts could be made. Therefore, rigorous solid waste characterizations were unmerited. Among the different facilities, different solid waste properties were often measured. As a result, use of these data to evaluate disposal properties as a function of process type is difficult because data are limited or nonexistent. Since this was not the objective of these studies, it should not be interpreted as a flaw in the analytical test matrix for the source test and evaluation studies. These data provided only limited support for engineering and planning for actual disposal at a given site for the individual gasifier wastes and by-products. The internal quality control procedures used in the Source Test and Evaluation Studies are presented in Appendix B.

TABLE 2. SOLID WASTE DATA SUMMARY FOR SOURCE TEST AND EVALUATION PROGRAMS

Source Tests and Evaluation Programs	Chemical Properties						Physical Characteristics							Leaching Tests		Bioassay Tests						
	Total Elemental Composition	Trace Element Composition	Organic Compounds	Proximate/Ultimate Analysis	Mineral Analysis of Ash	Radiochemistry	Particle Size Distribution	Specific Gravity	Particle Morphology	Bulk Density	Moisture Content	Ash Content	Specific Surface Area	Leaching/ RCRA Extract	Leaching/ ASTM Extract	Aquatic Acute Toxicity	Fresh Water Algae Toxicity	Mutagenicity	Cytotoxicity	Rodent Acute Toxicity	Soil Microcosm Test	Plant Stress Test
Chapman	X	X																X	X	X	X	X
Wellman-Galusha Fort Snelling	X	X		X		X								X				X	X	X		
Wellman-Galusha Glen-Gery	X	X	X	X		X	X	X	X					X								
Riley Gas Producer	X	X	X	X		X	X							X			X		X	X		
Foster Wheeler/ STOIC	X	X	X	X										X								
Lurgi-Type Kosovo	X	X	X	X				X			X	X	X	X	X			X	X			
Texaco (Ruhrchemie)	X	X	X	X	X	X	X	X		X						X	X			X		
Koppers-Totzek (Ptolemais)					X							X		X								
KRW	X	X	X	X		X	X	X		X	X	X		X	X							

Trends in data are classified by facility; this classification should not be interpreted to imply that resultant waste characteristics are solely dependent on the process. As stated in the introduction, feedstock and operating conditions have combined effects upon waste characteristics. This arbitrary facsimile is used then to represent not only the process, but the entire set of effective factors during an individual sampling event for a given process. These results might have been quite different if the same processes were monitored using different feedstocks and/or operating conditions. Solid wastes were not collected from a single process using different feedstocks or operating conditions; therefore, comparative data assessments of solid wastes based on feedstock or process conditions are absent from this report. Process data are discussed and evaluated for efficiency in Section 3 of this report.

GASIFIER ASH

Elemental analyses of gasifier ashes were reported for the eight facilities using several analytical techniques (1-8). Ash mineral analysis was available for three facilities tests (2,7,8). Proximate/ultimate analyses of seven gasifier ashes were performed (2-8). Radiochemical species were analyzed on five gasifier ashes (2,3,4,7,8). Organic priority pollutant concentrations were determined for five ashes (3,4,5,7,8). Particle size distribution of the ashes was available from four studies (3,4,7,8). Bulk density, specific gravity, and ash fusion temperature data were available from the Texaco (Ruhrchemie) study (7). Resource Conservation and Recovery Act (RCRA) Extraction Procedure (EP) was performed for eight ashes (1-8). Water quality parameters were analyzed on three of these EP extracts (2,4,7). Chemical composition and water quality data for the ASTM extracts of four ashes were determined (1,4,6,8). These data are summarized below.

Chemical Analysis of Gasifier Ashes

Elemental Analysis of Gasifier Ashes--

Spark source mass spectrographic (SSMS) analysis was performed on gasifier ashes produced from tests at the Riley, Texaco (Ruhrchemie), Lurgi-type (Kosovo), Wellman-Galusha (Fort Snelling, Glen Gery), Foster-Wheeler/STOIC, and Chapman facilities. This analytical method is generally considered a screening technique to provide semi-quantitative information about concentrations of minor and trace elements. To complement SSMS analysis, atomic absorption spectroscopy (AAS) and inductively coupled argon plasma emission spectroscopy (ICPES) were used to provide more precise data for some of the gasification systems. Limited ICPES data were available from Wellman-Galusha (Fort Snelling), Kellogg-Rust/Westinghouse (KRW), Texaco, Riley, and Foster-Wheeler/STOIC; AAS data were available for a few elements for the seven tests for which SSMS data were available. Summary data are presented by analytical technique in the remainder of this section. This approach is taken so that SSMS (semiquantitative) data and ICPES (quantitative) data are not directly compared. For processes having ICPES, AAS, and SSMS data, the more precise values for elemental concentrations are AAS, then ICPES, then SSMS. Because of these differences in analytical precision, trends in SSMS data are less reliable than trends in ICPES and AAS data.

SSMS--Analytical SSMS data for the seven processes are given in Table C-1 in the appendices. A summary of these data is given in Table 3. Concentration ranges of each element are given along with the identity of the process or facility associated with the lowest and highest concentrations of each element.

These data show the following trends:

- Aluminum, calcium, iron, magnesium, potassium, phosphorous, silicon, and titanium are major components (concentrations greater

TABLE 3. RANGE OF SPARK SOURCE MASS SPECTROGRAPHIC DATA FOR GASIFIER ASHES[a]

	Comparative Values		Element
Element	High	Low	Range (mg/Kg ash)
Aluminum	-[b]	-	MC[c]
Antimony	G	E	0.5-200
Arsenic	C	G	<0.4-62
Barium	-	-	MC
Beryllium	G	A	0.3-10
Bismuth[d]	E	F	<0.1-18
Boron	D	E	13-320
Bromine	C	D	2-77
Cadmium	F	B	0.3-5
Calcium	-	-	MC
Cerium	E	C	29-180
Cesium	B	A	2-12
Chlorine	B	E	8-130
Chromium	B	C	2-450
Cobalt	B	A,F	1-54
Copper	G	A	2-1000
Dysprosium	B,D	A,C	2-7
Erbium	B	A	0.7-10
Europium	B	A,C,E,F	1-4
Fluorine	C	E	59-720
Gadolinium	B	A,C,E	2-8
Gallium	G	D	9-50
Germanium	B	C	0.5-8
Gold	-	-	NR[e]
Hafnium	B	D	1-4
Holmium	D,F	C	0.6-4
Iodine	B,C	D	0.2-2
Iridium	-	-	NR
Iron	-	-	MC
Lanthanum	F	C	21-160
Lead	B	D	5-21
Lithium	E	A	6->240

(Continued)

TABLE 3. (Continued)

Element	Comparative Values High	Comparative Values Low	Element Range (mg/Kg ash)
Lutetium	B	D,E,F	.3-.4
Magnesium	-	-	MC
Manganese	B	E	69-<1000
Molybdenum	B	E	0.28-39
Neodymium	B	A	9-49
Nickel	C	F	3-180
Niobium	E	C	10-62
Osmium	-	-	NR or ND[f]
Palladium	-	-	NR or ND
Phosphorous	-	-	MC
Platinum	-	-	NR or ND
Potassium	-	-	MC
Praseodymium	B	A	4-31
Rhenium	-	-	NR or ND
Rhodium	-	-	NR or ND
Rubidium	G	A	16-2000
Ruthenium	-	-	NR or ND
Samarium	B	A	5-16
Scandium	B	F	2-50
Selenium	G	F	0.8-30
Silicon	-	-	MC
Silver	A	F	<0.3-3
Sodium	A,B,C,D,E	F	<170->1000
Strontium	A,D	C	320-2000
Sulfur	E	F	<420->10000
Tantalum[g]	B	F	<.8-1
Tellurium	B	E	<.2-6
Terbium	B	E	0.6-2
Thallium[d]	A	E	0.3-17
Thorium	B	C	0.5-30
Thulium	B	A,E,F	0.2-6
Tin	G	D,F	0.5-300

(Continued)

TABLE 3. (Continued)

Element	Comparative Values High	 Low	Element Range (mg/Kg ash)
Titanium	-	-	MC
Tungsten	B	D	1-3
Uranium	G	C	2-400
Vanadium	D	G	30-410
Ytterbium	B	A	1-4
Yttrium	B	C	17-140
Zinc	B	F	2-290
Zirconium	E	C	33-350

a Code used in this table to identify source test:
A Wellman-Galusha (Fort Snelling)
B Chapman
C Foster-Wheeler/STOIC
D Lurgi-type (Kosovo)
E Riley
F Texaco
G Wellman-Galusha (Glen Gery)

b Data reported only as "major component" or "greater than" 1000 mg/kg for 6 of the 7.

c MC = Major component.

d No data for C, D, G.

e NR = Not reported.

f ND = Not detected.

g No data for A, C, E, G.

than 1000 mg/kg) in the gasifier ashes from at least six of the seven test facilities;

- Conversely, osmium, palladium, platinum, rhenium, rhodium, and ruthenium were generally undetected in all of the gasifier ashes;
- The Chapman process facility produced a gasifier ash with the highest concentrations of cesium, chlorine, chromium, cobalt, erbium, europium, gadolinium, germanium, hafnium, lead, manganese, praseodymium, samarium, sodium, tantalum, tellurium, terbium, thorium, thulium, tungsten, ytterbium, and zinc;
- The Riley process produced a gasifier ash with the highest concentrations of bismuth, cerium, lithium, niobium and zirconium;
- The Texaco process (Ruhrchemie) produced a gasifier ash with the highest concentrations of cadmium, holmium and lanthanum;
- The Foster-Wheeler/STOIC process produced a gasifier ash with the highest concentrations of arsenic, bromine, fluorine, iodine and sodium;
- The Wellman-Galusha (Fort Snelling) process produced a gasifier ash with the highest concentrations of silver, sodium, strontium, and thallium;
- The Lurgi-process (Kosovo) produced a gasifier ash with the highest concentrations of boron, holmium, sodium, strontium and vanadium; and
- The Wellman-Galusha (Glen Gery) process produced a gasifier ash with the highest concentrations of antimony, beryllium, copper, gallium, scandium, selenium, tin, and uranium.

ICPES--Analytical ICPES data are given in Table C-2 in the appendices. A summary of these data is given in Table 4. Concentration ranges for each element analyzed by ICPES are given along with the identity of the process or facility associated with the lowest and the highest concentrations of each element.

These data show the following trends:

- Aluminum, calcium, iron, magnesium, potassium, sodium and titanium are major components (concentrations greater than 1000 mg/Kg) in all source tests;
- The Riley process produced a gasifier ash with the highest concentrations of barium, calcium, magnesium, and sodium; and
- The Texaco process produced a gasifier ash with the highest concentrations of boron, chromium, iron and nickel.

AAS--A summary of results from the atomic absorption spectrophotometric analysis of gasifier ashes is given in Table C-3 in the appendices. These data are somewhat sparse for the seven facilities with SSMS data available. Only arsenic and antimony were analyzed by AAS for all seven facilities. The arsenic concentration ranged from 3 mg/Kg ash at the Wellman-Galusha facility at Glen Gery up to 75 mg/Kg ash for the Lurgi-type (Kosovo) facility. Antimony concentrations ranged from less than detection limit values at Foster-Wheeler/STOIC, Kosovo, Ruhrchemie, and Fort Snelling facilities to a high value of 200 mg/Kg ash for the Chapman facility.

Although the elemental characterization of gasifier ashes by SSMS, ICPES, and AAS are available, these data often provide conflicting information as shown in Table 5. If the trends observed for the results from SSMS

TABLE 4. RANGES OF INDUCTIVELY COUPLED ARGON PLASMA EMISSION SPECTROGRAPHIC DATA FOR GASIFIER ASHES[a,b]

Element	Comparative Values High	Comparative Values Low	Element Range (mg/Kg ash)
Aluminum	E	A	18,900 - 86,000
Barium	D	G	96 - 3,400
Boron	B	D,E	110 - 820
Calcium	D	F	29,000 - 96,000
Chromium	B	D	<0.2 - 160
Cobalt	G	C	12 - 120
Copper	E	C	32 - 80
Iron	B	A	30,000 - 81,000
Magnesium	D	F	4,400 - 22,000
Manganese[c]	G	F	19 - 2,200
Nickel	B	D	26 - 130
Potassium[c]	F	E	4,400 - 13,000
Sodium	D	C	1,500 - 24,000
Titanium	B	A	1,200 - 5,200
Vanadium	B	A	37 - 180
Zinc	E	A	4.6 - 380

[a] Data for antimony, arsenic, cadmium, lead, molybdenum, silver, strontium, and tin are not given due to lack of reliable data.

[b] Code used in this table to identify source test:
A Wellman-Galusha (Fort Snelling)
B Texaco
C Foster-Wheeler/STOIC
D Riley
E KRW-WY Subbituminous
F KRW-Pittsburgh #8
G KRW-ND lignite

[c] High and low values were obtained while testing different coal types in the KRW gasifier.

TABLE 5. COMPARISON OF SSMS, ICPES, AND AAS DATA FOR GASIFIER ASHES (mg element/Kg ash)

Element	Facilities With Highest Concentrations		
	SSMS	ICPES	AAS
Boron	Lurgi-Type (Kosovo) (320)	Texaco (820)	
Chromium	Chapman (450)	Texaco (160)	Lurgi-type (180)
Cobalt	Chapman (54)	KRW (120)[a]	
Copper	Wellman-Galusha (Glen Gery) (1000)	KRW (80)[b]	
Manganese	Chapman (MC)	KRW (2200)[a]	
Nickel	Foster Wheeler/STOIC (180)	Texaco (130)[b]	Lurgi-type (Kosovo) (320), Texaco (120)
Vanadium	Lurgi-type (Kosovo) (410)	KRW (130)[b]	Lurgi-type (Kosovo) (100)
Zinc	Chapman (290)	KRW (380)[b]	

[a] ND lignite
[b] WY subbituminous

are compared with the trends observed for ICPES and AAS, the following discrepancies become apparent:

- Boron concentrations by SSMS appear lower than by ICPES, chromium concentrations are much lower by ICPES and AAS than by SSMS;
- Copper concentrations are much lower by ICPES than by SSMS;
- Vanadium concentrations are much lower by ICPES and AAS than by SSMS;
- Nickel data agree for SSMS and ICPES.

Theoretically, similar values for elemental concentrations should be obtained by all three analytical techniques. However, these discrepancies in the measured values illustrate differences in analytical response of these methods for elements in the gasifier ashes. Each analytical technique is susceptible to a different array of interferences and instrumental constraints. These interferences and constraints are also different for individual instruments.

In most cases, ICPES and AAS data are considered to be "better" values for elemental concentrations than SSMS; therefore, conclusions should be drawn preferentially from these data when they are available.

When values for elemental concentrations in ashes from this series of source tests are compared to elemental compositions found in other gasifier ashes, ranges of elements in the waste residues are generally similar (12,13). Other studies have shown that slags produced from gasification and conventional combustion are also similar (13). These results suggest that gasifier slags may not require solid waste management practices substantially different from those currently used for coal combustion solid wastes (10,12) solely based on the elemental compositional data for the slags.

Ash Mineral Analysis of Gasifier Ash--Ash mineral analyses were available from the Wellman-Galusha (Fort Snelling) ash and the Texaco (Ruhrchemie) ash and Koppers-Totzek (Ptolemais). These data are given in Table C-4 in the appendices. Constituents with concentrations greater than 10 percent were SiO_2, Al_2O_3, and Fe_2O_3 for both ashes. Constituents with concentrations between 1 and 10 percent included TiO_2, CaO, MgO, K_2O, Na_2O, and SO_3. Only traces of P_2O_5, SrO, BaO, and Mn_3O_4 were present. Undetermined oxides accounted for over 2% of the Wellman-Galusha (Fort Snelling) oxide content and over 12% in the Koppers-Totzek (Ptolemais).

Proximate/Ultimate Analysis of Gasifier Ashes--Proximate/ultimate analyses were performed on eight gasifier ashes. These data are given in Table C-5 in the appendicies. Summary ranges are given in Table 6. These data show the following:

- Wellman-Galusha (Glen-Gery) gasifier ash had the highest percent fixed carbon;
- Riley gasifier ash had the highest percent volatiles, Btu/lb, percent carbon, and percent hydrogen;
- Lurgi-type (Kosovo) gasifier ash had the highest percent ash, and percent oxygen;
- Texaco (Ruhrchemie) gasifier ash had the highest percent nitrogen and chlorine;
- KRW-ND lignite gasifier ash had the highest percent sulfur.

Ultimate/proximate data for the gasifier ashes indicate large variation in results due to feedstock, process type, and process conditions. While these data show low sulfur retention in the solid wastes for the processes,

TABLE 6. RANGES OF RESULTS FROM PROXIMATE/ULTIMATE ANALYSIS OF GASIFIER ASHES

	Facilities[a]		
	Comparative Values		
Analysis	High	Low	Range
PROXIMATE			
Ash (%)	E	B	24.7-95
Volatile (%)	C	G	0.57-10.59
Fixed Carbon (%)	B	H	0.81-71.76
ULTIMATE			
Btu/lb (Kcal/Kg)	C	H	710-4,993 (394-2774)
Carbon (%)	C	E	1.8-35.36
Hydrogen (%)	C	H	0.07-0.61
Nitrogen (%)	F	E	0.03-0.7
Chlorine (%)	F	D	0-0.05
Sulfur (%)	G	E	0.15-4.42
Ash (%)	E	C	62.54-95
Oxygen (%)	E	C,F,G,H	0-2.3

[a] Code used in this table to identify source test:
A = Wellman-Galusha (Fort Snelling)
B = Wellman-Galusha (Glen-Gery)
C = Riley
D = Foster Wheeler/STOIC
E = Lurgi-type (Kosovo)
F = Texaco (Ruhrchemie)
G = KRW-Pittsburgh #8
H = KRW-ND lignite

the Btu/lb values for these wastes indicate that incomplete reaction may be a problem. Speculatively, this may significantly decrease as commercial gasifiers are operated at preferred conditions over a long-term burn, and start up problems, lack of steady state conditions, and inability to operate under preferred conditions are no longer test considerations.

Radioactive Species Analysis--For the Wellman-Galusha (Fort Snelling) and Riley facilities, 15 radioactive species were measured. These data are given in Table C-6 in the appendices. Elemental radioactive species present in these two ashes with activities greater than one picoCurie per gram included Radium-226, Uranium-234, Uranium-238, Potassium-40, Lead-214, Bismuth-214, Thorium-228, Thorium-230, and Thorium-232.

Dependent on new regulations for utility wastes, radioactive species concentrations in slags may or may not pose a special problem. It has long been established that fly ash from conventional coal combustion often contains these same species and other radioactive species that are commonly found in secular equilibrium with daughter species of uranium and thorium. Detectable levels of radioactive species are commonly found in gasifier slag as noted above. These species are also present in natural coal, rocks, and soils, but typically are more highly concentrated in coal ash due to combustion of the non-mineral fraction of the coal.

Gas Chromatograph-Mass Spectrographic Analysis--Ashes from Wellman-Galusha (Glen Gery), Riley, Foster Wheeler/STOIC, Texaco (Ruhrchemie) and KRW were analyzed for base-neutral extractable compounds, acid extractable compounds, and synfuel compounds. These data are given in Table C-7 in the appendices. In the priority pollutant category "Appendix A Base/Neutral Extractable Compounds," the following compounds were detected in the gasification facility listed:

- Acenaphthene--KRW ash,

- Bis(2-ethyl)phthalate--Riley, Wellman-Galusha (Glen Gery), Foster-Wheeler/STOIC and Texaco,

- 4-Bromophenyl phenyl ether--Riley,

- Chrysene--Riley ash,

- Diethyl phthalate and di-n-butyl phthalate--Riley and Wellman-Galusha (Glen Gery) ashes,

- Fluoranthene - Riley ash,

- Fluorene - KRW ash,

- 1,2-Diphenyl hydrazine--Riley ash,

- Naphthalene--Riley and Foster Wheeler/STOIC, and KRW ashes,

- Phenanthrene--Riley and KRW ashes, and

- Pyrene--Riley ash.

All other priority pollutants were below detection limits for the ashes. In the "Appendix A Acid Extractable Category," only 2,4,6-trichlorophenol was present in the KRW ashes above the detection limits. In the "Appendix C Extractable Category," n-alkanes (C_{10}-C_{30}) and cumene were identified in the Riley ash. Biphenyl was present in the KRW ashes. Concentrations for all other compounds fell below detection limits. Benzothiophene was present in the KRW ashes as listed in Table C-7 under "synfuels compounds".

The GC-MS data on gasifier slag should be carefully scrutinized. All phthalate pollutant concentrations may possibly be due to contaminants introduced from plastic containers. In other studies, detectable phthalate concentrations have been observed in column leachates from ash materials in lucite columns; these contaminants disappear when glass containers are used. However, plastic containers do not account for hydrazine, naphthalene, and pyrene compounds in the slag. Some of these compounds may be destroyed if gasification is performed with increased efficiency. Thermal destruction of organic compounds can be complete; however, there are limits to destruction efficiency based on the actual chemistry of combustion and the actual process. Obviously, complete thermal destruction of organics is not the primary goal of gasification and it is likely that there will always be some organic residue.

Physical Properties Determinations

Physical properties data are given in Table C-8 in the appendices. Bulk densities were measured on two samples of ash from the Texaco (Ruhrchemie) test. The compacted density was not significantly higher than the uncompacted density (43 lb/ft^3 or 0.32 g/m^3) for the Texaco (Ruhrchemie) gasifier ash. The particle specific gravity of the Texaco ash averaged 2.2. The apparent bulk density of the KRW ashes ranged for 1.83 to 2.11.

The ash fusion temperature for initial deformation of the Texaco (Ruhrchemie) ash averaged 2070°F (1132°C) for a reducing atmosphere. Softening occurred between 2070°F (1132°C) and 2095°F (1146°C), and the ash became fluid at 2160-2120°F (1182-1160°C).

Particle size distribution data were available from the Texaco (Ruhrchemie) study, the Wellman-Galusha (Glen Gery) study, the Riley study, and the KRW study. The ash from the Glen Gery study was sized completely between particle diameters 14 mm and 75 mm. The Riley ash had 50 percent of the particles sized in the 12.5 mm-6.3 mm range with 30 percent of the remaining material falling in the range of 2 mm-6.3 mm. About 40 percent of the particles from the Texaco ash were larger than 0.7 mm, with about 10 percent of the particles larger than 2 mm. The KRW ashes had a concentrated fraction of particles in the 0.4 to 0.8 mm size range.

Physical characteristics are mainly process dependent, but can be dependent on the feed coal particularly for the ash fusion temperature. Perhaps the largest void in gasifier ash properties are data required for design of a disposal site for solid waste; i.e., physical and engineering properties. Available densities and particle size distribution data for the gasifier ashes indicate that they are closer to conventional combustion bottom ash than fly ash properties.

Evaluation of Leaching Potential

RCRA Leaching--

The RCRA EP (11) was performed on all ten ashes. These data are given in Table C-9 in the appendices and are augmented with data from the Lurgi SASOL I (15) test, and an IGT U-Gas test (16). These data are summarized in Table 7. As shown in Table 7, extracts of these ashes did not exceed the RCRA Maximum Permissible Limit; in fact, most concentrations were substantially lower than these limits.

These RCRA EP extracts were also analyzed for elements not specified in the RCRA procedure. These analytical results are shown in Table C-10 in the appendices. Summary ranges for these data are also given in Table 7. The following trends were observed:

- Chapman RCRA ash leachate had the highest concentrations of selenium and titanium;

- Wellman-Galusha (Fort Snelling) RCRA ash leachate had the highest concentrations of magnesium, manganese, potassium, silicon, strontium, and titanium;

TABLE 7. SUMMARY RANGES OF CHEMICAL CONCENTRATIONS OF ELEMENTS IN RCRA EP EXTRACTS FROM GASIFIER ASHES (mg/L)

Elements	Facilities[a]		Range	RCRA Limit
	High	Low		
Aluminum	F	A	<BC[b]-0.15	
Antimony	-[c]	-	<0.005-<0.050	
Arsenic	D	G,H	<0.002-0.033	5
Barium	K	F	0.019-7.2	100
Beryllium	-	-	<0.0005-<0.002	
Cadmium	L	D,F	<0.0005-0.1	1
Calcium	B	C	0.099-MC[d]	
Chromium	E	D,G	<0.001-0.3	5
Cobalt	F	A	<BC-3.3	
Copper	B	D,G	<0.001-0.1	
Iron	E	D	<0.008-10	
Lead	H	D,F,G,L	<0.002-0.025	5
Lithium	G	A	ND[e]-0.29	
Magnesium	B	C	0.036-MC	
Manganese	B	E	0.001-0.5	
Mercury	-	-	<0.0002-<0.0005	0.2
Molybdenum	E	A	<BC-0.1	
Nickel	B,E	A	<BC-0.04	
Potassium	B	I	ND-MC	
Selenium	A	C	<0.001-0.01	1
Silicon	B	C	0.2-MC	
Silver	K	D	<0.0005-0.007	5
Sodium	D	F	1.6-140	
Strontium	B	C	0.06-6	
Titanium	A,B	G,I	<0.005-0.1	
Vanadium	E	A	ND-0.07	
Zinc	C	A	<BC-4	

If analytical values for an element are available from both Tables C-9 and C-10, values from Table C-9 take precedence.

[a] Code used in this table to identify source test:

A Chapman
B Wellman-Galusha (Fort Snelling)
C Wellman-Galusha (Glen Gery)
D Riley
E Lurgi Type (Kosovo)
F Texaco (Ruhrchemie)
G Lurgi (SASOL 1)
H IGT U-Gas
I KRW-WY Subbituminous
J KRW-Pittsburgh #8
K KRW-ND lignite
L Foster-Wheeler/STOIC

[b] <BC = less than or equal to blank concentration.

[c] All analyses below detection limit.

[d] MC = Major component.

[e] ND = Not detected.

- Wellman-Galusha (Glen Gery) RCRA ash leachate had the highest concentrations of zinc;
- Riley RCRA ash leachate had the highest concentrations of arsenic, beryllium, calcium, and sodium;
- Lurgi-type (Kosovo) RCRA ash leachate had the highest concentrations of chromium, iron, molybdenum, nickel, and vanadium;
- Lurgi (SASOL I) RCRA ash leachate had the highest concentrations of lithium; and
- KRW RCRA ash leachates had the highest concentrations of barium and silver.

Validity of measuring water quality parameters on RCRA EP extracts should be viewed from two opposing positions. First, because EP extracts were the only aqueous extracts for many of the materials tested, trying to determine water quality seems reasonable. However, one must at the same time realize that this extract undergoes pH adjustment with up to 400 mL of 0.5N acetic acid. This addition obviously affects resultant pH, the total dissolved solids, and the total organic carbon (acetate addition).

Water quality parameters in RCRA EP extracts of gasifier ashes were measured for Wellman-Galusha (Fort Snelling), Riley, Texaco (Ruhrchemie) and IGT U-Gas ashes (see Table C-11 in appendices). These data are sparse for each parameter (1-4 points). The pH ranged from 4.13 (Fort Snelling) to 9.5 (Riley). Total organic carbon (2 data points) ranged from 95 mg/L (IGT U-Gas) to 474 mg/L (Riley). Chloride (2 data points) ranged from 0.8 mg/L (IGT U-Gas) to 45 mg/L (Riley). Fluoride (2 data points) ranged from <0.02 mg/L (IGT U-Gas) up to 1.03 mg/L (Riley). Total dissolved solids (3 data points) ranged from 185 mg/L (IGT U-Gas) up to 213 mg/L (Fort Snelling). Nitrate (3 data points) ranged from 0.37 mg/L (IGT U-Gas) up to 23 mg/L (Riley). Sulfate (2 data points) ranged from 2 mg/L (IGT U-Gas) to 580 mg/L

(Riley). Ammonia (3 data points) ranged from <0.007 (Fort Snelling) up to 0.11 mg/L (IGT U-Gas). Cyanide was below analytical detection limits in three ashes. Phosphate (3 data points) ranged from <0.01 mg/L (Fort Snelling) up to 1.3 mg/L (Riley). Phenol (4 data points) ranged from 0.002 mg/L (Fort Snelling) up to 0.016 mg/L (IGT U-gas). Biological oxygen demand (2 data points) ranged from 986 (Riley) to 2970 mg/L (Fort Snelling).

ASTM Extracts of Gasifier Ash--

Nine gasifier ashes were extracted by the ASTM extraction procedure (17). Analytical data for these extracts are given in Table C-12 in the appendices. Data for different elements are usually incomplete for all five ashes. Using available data only, the following trends were observed:

- Riley ASTM ash extract had the highest concentrations of aluminum (7.6 mg/L), cobalt (0.009 mg/L), potassium (0.04 mg/L), sodium (130 mg/L), strontium (3 mg/L), and vanadium (0.045 mg/L);

- Lurgi-type (Kosovo) ASTM ash extract had the highest concentrations of arsenic (0.01 mg/L), chromium (0.5 mg/L), iron (0.1 mg/L), lead (0.07 mg/L);

- Lurgi (SASOL I) ASTM ash extract had the highest concentrations of calcium (330 mg/L), lithium (1.1 mg/L), magnesium (11 mg/L), manganese (0.045 mg/L), molybdenum (0.096 mg/L), potassium (83 mg/L), and selenium (0.008 mg/L);

- IGT U-Gas ASTM ash extract had the highest concentrations of antimony (0.002 mg/L), silver (0.003 mg/L), and zinc (0.15 mg/L);

- KRW ASTM ash extracts had the highest concentrations of barium (20 mg/L), boron (1.3 mg/L), cadmium (0.004 mg/L), iron (26 mg/L), phosphorous (0.82 mg/L), silicon (20 mg/L), and titanium (0.6 mg/L); and

- Concentrations of beryllium, cadmium, and mercury were below analytical detection limits for all nine ASTM extracts of gasifier ashes.

Water quality parameters in ASTM extracts of six gasifier ashes were measured; these data are in Table C-13 in the appendices. Again, these data are quite limited. The initial pH ranged from 5 to 10.7 in the six extracts. The final pH ranged from 8.4-10.6. Alkalinity as $CaCO_3$ ranged from 14 mg/L to 97 mg/L. Total organic carbon ranged from <1 mg/L up to 7.2 mg/L. Chemical oxygen demand ranged from 5 mg/L to 44 mg/L. Chloride concentrations ranged from 1.9 mg/L to 19 mg/L. Fluoride concentrations ranged from <0.02 to 0.57 mg/L. Total dissolved solids ranged from 115 mg/L to 1820 mg/L. The conductivity ranged from 220 μmhos/cm^2 up to 1530 μmhos/cm^2. Nitrate concentrations ranged from 0.3 mg/L to 23 mg/L. Total phosphate concentrations ranged from 0.03 mg/L to 0.92 mg/L. Phenol was consistently undetected. The rest of these data consisted of one to two data points per parameter; therefore, ranges are not given for these parameters (see Table C-13).

Leachable organic compounds were analyzed for two KRW ashes (Table C-20 in the appendices). The only detectable organic compound identified was aniline (4 ug/L) in the Pittsburgh #8 composite only.

In evaluation of possible environmental problems from leaching of these wastes, the RCRA EPs and the ASTM extracts did not exceed the established criteria. Although ash-slags would be classified as "non-hazardous" under currently proposed RCRA criteria, soil attenuation experiments would permit a better assessment of actual impacts to affected ground and surface water systems. Studies of this type are already underway by Oak Ridge National Laboratory (11). In general, leaching studies of gasifier ashes have shown that both inorganic elements and polynuclear aromatic hydrocarbons in the leachates are relatively low and at this time appear not to be of significant environmental concern (20). The major environmental impact associated with disposal of these wastes may be the sulfate dissolution and potential acidification of groundwater. However, Illinois Geological Survey studies of soil attenuation of soluble constituents leached from coal conversion solid wastes have shown that soil properties control the degree of attenuation to a greater extent than the chemical composition of the waste leachates (20).

Percent Soluble Elements--

The percent of the total of each element soluble in RCRA and ASTM extracts were calculated for the EPA source test programs (1-7) where data were available. The following trends in these data were observed:

- For Chapman gasifier ash, the elements soluble in the RCRA EP extract at greater than one percent of the ash content were: arsenic (25%), barium (2%), iron (10%), lead (1%), potassium (100%), silicon (2%), and strontium (3%); in the ASTM extract none were above 1%.

- For Wellman-Galusha (Fort Snelling) gasifier ash, the elements in the RCRA EP extract at greater than one percent of the ash content were: barium (1%), cadmium (2%), copper (6%), manganese (16%), nickel (1%), sodium (100%), strontium (38%), and zinc (8%).

- For Wellman-Galusha (Glen Gery) gasifier ash, the elements soluble in the RCRA EP extract at greater than one percent of the ash content were: arsenic (2%), barium (≤2%), cadmium (5%), lead (1%), molybdenum (100%), potassium (12%), selenium (1%), silicon (4%), sodium (2%), and zinc (100%).

- For Riley gasifier ash, the elements soluble in the RCRA EP extract at greater than 1 percent were: arsenic (100%), calcium (30%), chromium (10%), calcium (100%), magnesium (2%), molybdenum

(5%), nickel (1%), potassium (4%), selenium (12%), sodium (10%), vanadium (1%), and zinc (2%); in the ASTM extract greater than 1% included antimony (1%), beryllium (2%), chromium (2%), molybdenum (1.2%), and silver (2%).

- For Lurgi-type (Kosovo) gasifier ash, the elements soluble in the RCRA EP extract at greater than 1 percent of the ash content were: aluminum (10%), barium (100%), chromium (3%), iron (100%), lithium (100%), manganese (100%), molybdenum (22%), silicon (100%), strontium (22%), titanium (100%), vanadium (1%), and zinc (5%); in the ASTM extract greater than 1% included aluminum (100%), barium (100%), chromium (1%), iron (100%), lithium (100%), manganese (100%), molybdenum (2%), silicon (100%), titanium (100%), and zinc (2%).

- For the Texaco (Ruhrchemie) gasifier slag, the elements soluble in the RCRA extract at greater than 1 percent of the slag content were: antimony (8%), beryllium (1%), cadmium (2%), cobalt (100%), copper (3%), and silver ($\leq$2.8%).

- Data were unavailable for Foster Wheeler/STOIC.

Bioassay--

Bioassay tests are currently not used to evaluate the disposal of other solid wastes; therefore there is no basis for comparison of bioassay tests performed on gasifier wastes. Hence, these data are not shown in Section 4 or the appendices. However, a summary discussion of these results is given below.

In the Riley gasifier study, the ash was shown to be non-mutagenic in the presence or absence of metabolic activation in the Ames test. The ash leachate had low toxicity rabbit alveolar microphage (RAM-test) and no detectable toxicity using the in vitro CHO test. However, freshwater aquatic bioassay tests showed a high degree of toxicity towards the alga *Selenastium capricornutum*.

In the Texaco (Ruhrchemie) study, the gasifier ash gave a negative response (no mutagenicity) in the Ames test, little or no detectable cytotoxicity in the RAM assay, and no apparent acute toxicity in the RAT tests.

The ash from the Lurgi-type (Kosovo) facility was determined not to be a very mutagenic substance giving a negative Ames test response. However, in vitro cytotoxicity produced an EC_{50} of <600.

For the Chapman ash, the Ames test was negative and the rodent acute toxicity (RAT) was low.

For the Wellman-Galusha (Fort Snelling) gasifier, the ash gave a negative Ames response with no RAM or rodent toxicity.

In other bioassays of gasifier ash, no positive results were given in the Ames tests. Daphnia toxicity was observed for some gasifier leachates (20).

CYCLONE DUST

Elemental analyses of cyclone dust or scrubber fines were reported in six facilities using several techniques (2-7). The Texaco (Ruhrchemie) facility used a venturi scrubber to remove particles entrained in the product gas. In terms of process configuration, the scrubber fines are equivalent to the cyclone dust in the other facilities. Ash mineral analysis was available for two facilities' tests (2,7). Proximate/ultimate analyses of seven gasifier cyclone dusts were performed (1-7). Radiochemical species were analyzed for four cyclone dusts (2,3,4,7). Organic priority pollutant concentrations were determined for four cyclone dusts (3,4,5,7). Particle size distributions for the cyclone dusts were available for three studies (3,4,7). Bulk density, specific gravity, and ash fusion temperatures were measured for Texaco (Ruhrchemie) scrubber fines. The RCRA EP was performed on six cyclone dusts (1,2,3,4,5,7). Water quality parameters were analyzed on four of these EP extracts (2,3,4,7). Data for the chemical composition and water quality parameters of ASTM extracts were available for Riley and Texaco (Ruhrchemie) respectively (4,7). These data are summarized below.

Chemical Analysis of Cyclone Dusts

Spark source mass spectrographic (SSMS) analysis was performed on cyclone dusts produced from the tests at Wellman-Galusha (Fort Snelling and Glen Gery), Riley, Foster Wheeler/STOIC, Lurgi-type (Kosovo), and Texaco (Ruhrchemie) facilities. SSMS is generally considered a semi-quantitative technique for screening minor and trace element concentrations. To compliment and alleviate some of the shortcomings of SSMS analysis, atomic absorption spectroscopy (AAS) and inductively coupled argon plasma emission spectroscopy (ICPES) were used to provide more accurate data for some of the gasification systems. Limited ICPES data were available from Wellman-Galusha (Fort Snelling), Foster Wheeler/STOIC, and Texaco (Ruhrchemie); AAS data were available for a few elements from six tests (Kosovo omitted) for which SSMS data were available. Summary data are presented by analytical technique in the remainder of this section.

SSMS--

Analytical SSMS data for six processes are given in Table D-1 in the appendices. A summary of these data is given in Table 8. Concentration ranges of each element are given along with the identity of the facility associated with the highest and lowest concentrations of each element.

TABLE 8. RANGE OF SPARK SOURCE MASS SPECTROGRAPHIC DATA FOR CYCLONE DUSTS

Element	Comparative Values[a]		Element
	High	Low	Range (mg/Kg dust)
Aluminum	C,D,E,F	A	100->1000
Antimony	A	D	2-100
Arsenic	C	A	<0.4-83
Barium	C,D,E,F	A	500->1000
Beryllium	C	B	0.4-3
Bismuth	C	D	0.2-5
Boron	A	E	7-400
Bromine	B	C	2-9
Cadmium	E	D	<0.1-3
Calcium	-[b]	-	All>1000
Cerium	C	B	15-99
Cesium	F	E,B	0.7-19
Chlorine	C	F	26-100
Chromium	F	B	11-450
Cobalt	F	E	1-20
Copper	A	D	12-900
Dysprosium	D,E	B	0.6-4
Erbium	F	B	0.3-4
Europium	F	B	0.4-2
Fluorine	E,F	A	100->1000
Gadolinium	F	B	0.4-3
Gallium	E	A	<10-280
Germanium	F	D	2-26
Gold	-	-	ND[c]
Hafnium	C	B	<0.1-3
Holmium	F	B	0.4-2
Iodine	C	B	0.4-24
Iridium	-	-	ND

(Continued)

TABLE 8. (Continued)

Element	Comparative Values[a]		Element Range (mg/Kg dust)
	High	Low	
Iron	-	-	All>1000
Lanthanum	C	B	8-130
Lead	E	B	8-870
Lithium	C	A	2-160
Lutetium	C,F	B	<0.1-0.3
Magnesium	C,D,E,F	A	500->1000
Manganese	F	E	97-600
Molybdenum	F	D	4-66
Neodymium	C	B,E	2-110
Nickel	F	B,E	3-190
Niobium	C	B	4-52
Osmium	B	C,D	<0.1-5
Palladium	-	-	ND
Phosphorous	-	-	All>1000
Platinum	-	-	ND
Potassium	-	-	All>1000
Praseodymium	C	B	2-35
Rhenium	-	-	ND
Rhodium	-	-	ND
Rubidium	F	A,B	3-150
Ruthenium	-	-	ND
Samarium	F	B	2-12
Scandium	F	E	1-34
Selenium	C,F	D	3-16
Silicon	-	-	All >1000
Silver	C	D	<0.1-5
Sodium	-	-	>480->1000
Strontium	D	A	50->1000
Sulfur	C,E,F	A	300->1000
Tantalum	F	B,C,D,E	<0.1-1
Tellurium	E	B,D	0.2-1
Terbium	E	B	0.1-0.8

(Continued)

TABLE 8. (Continued)

Element	Comparative Values[a] High	Comparative Values[a] Low	Element Range (mg/Kg dust)
Thallium	C	B	0.9-22
Thorium	C	B	2-97
Thulium	F	B	<0.1-0.4
Tin	E	D	0.8-77
Titanium	C,D,E,F	A	200->1000
Tungsten	C	B	<0.7-5
Uranium	F	B	0.9-46
Vanadium	C,F	B	19-150
Ytterbium	F	E	<0.6-3
Yttrium	F	D	7-77
Zinc	C	D	60->1000
Zirconium	C	B	29-110

a Code used in this table to identify source test:
A = Wellman-Galusha (Fort Snelling)
B = Wellman-Galusha (Glen-Gery)
C = Riley
D = Foster-Wheeler/STOIC
E = Lurgi-type (Kosovo)
F = Texaco (Ruhrchemie)
b Comparative data not available.
c ND = None detected.

These data show the following trends:

- Calcium, iron, phosphorous, potassium, sodium, and strontium are major components (>1000 mg/kg ash) in the cyclone dusts from all six facilities;

- Conversely, gold, iridium, osmium, palladium, platinum, rhenium, rhodium, ruthenium, and silver were undetected in all six cyclone dusts;

- The Wellman-Galusha (Fort Snelling) facility produced a cyclone dust with the highest concentrations of antimony, boron, and copper;

- The Wellman-Galusha (Glen Gery) facility produced a cyclone dust with the highest concentrations of aluminum and bromine;

- The Riley facility produced a cyclone dust with the highest concentrations of arsenic, beryllium, bismuth, chlorine, lanthanum, and zinc (among others);

- The Foster Wheeler/STOIC facility produced a cyclone dust with the highest concentrations of aluminum, barium, dysprosium, magnesium, strontium, and titanium;

- Lurgi-type (Kosovo) facility produced a cyclone dust with the highest concentrations of aluminum, barium, cadmium, dysprosium, fluorine, gallium, lead, magnesium, sulfur, tellurium, tin, and titanium;

- The Texaco (Ruhrchemie) facility produced scrubber fines with the highest concentrations of aluminum, barium, cesium, chromium, cobalt, erbium, europium, fluorine, germanium, holmium, manganese, molybdenum, nickel, rubidium, samarium, scandium, selenium, sulfur, tantalum, terbium, thullium, titanium, uranium, vanadium, ytterbium, and yttrium.

ICPES--

Analytical ICPES data are given in Table D-2 in the appendices for Wellman-Galusha (Fort Snelling), Foster-Wheeler/STOIC, and Texaco (Ruhrchemie). These data show the following trends:

- Wellman-Galusha (Fort Snelling) facility produced a cyclone dust with the highest concentrations of barium (2,300 mg/Kg dust), iron (7,900 mg/Kg), magnesium (12,300 mg/Kg dust), and strontium (1,180 mg/Kg dust);

- Foster Wheeler/STOIC facility produced a cyclone dust with the highest concentration of silver (690 mg/Kg dust);

- Texaco (Ruhrchemie) facility produced scrubber fines with the highest concentrations in mg element per Kg dust of aluminum (83,000), antimony (8.2), arsenic (60), beryllium (19), boron (1040), cadmium (13.2), calcium (29,000), chromium (200), copper (71), lead (220), manganese (380), molybdenum (130), nickel (130), phosphorous (2,900), potassium (16,000), selenium (29), silicon (150,000), sodium (7,300), titanium (5,600), vanadium (140), and zinc (1,750).

AAS--

A summary of results from atomic absorption spectrophotometric analysis of cyclone dusts is given in Table D-3 in the appendices. These data are sparse with data gaps for the six facilities in cadmium, lead, mercury, nickel, selenium, and silver concentrations. Only arsenic and antimony were analyzed for all six cyclone dusts. The arsenic concentration ranged from <0.4 mg/Kg dust at the Chapman facility up to 85 mg/Kg dust for the

Wellman-Galusha (Glen Gery) facility. Antimony concentrations ranged from <0.4 mg/Kg dust at the Wellman-Galusha (Fort Snelling) facility to a high value of 100 mg/Kg dust for the Chapman facility.

The same problems inherent with the variations in elemental concentrations determined using different analytical techniques discussed under gasifier ash in the beginning of Section 5 are equally applicable to cyclone dusts. Therefore, discrepancies in data trends based on SSMS results and ICPES results do exist and soluble fractions calculated from analytical results of different analytical techniques should be carefully scrutinized.

Elemental concentration ranges in cyclone dusts from these source tests are comparable to ranges found in other gasifier wastes analyzed in other studies (8). The cyclone dust is also similar in composition to the gasifier ash. Elements enriched in the cyclone dusts included lead, tin, zinc, antimony, and arsenic for most of the EPA Source Testing of gasifiers.

The cyclone dust, the finest fraction of the gasifier solid waste, resembles conventional fly ash (9). These wastes have also been shown to be morphologically similar based on scanning electron micrographs (9). This similarity extends to major oxide constituents: SiO_2, Al_2O_3, Fe_2O_3, and CaO.

Ash Mineral Analysis of Cyclone Dusts--Ash mineral analyses were available for Wellman-Galusha (Fort Snelling) cyclone dust and Texaco (Ruhrchemie) scrubber fines. These data are given in Table D-4 in the appendices. Constituents reported as oxides with concentrations greater than ten percent were SiO_2 and Al_2O_3 for both materials, Fe_2O_3 for Texaco only, and CaO and SO_3 for Wellman-Galusha only. Minor components (>1%) in the two dusts/fines included MgO and Na_2O. Traces of TiO_2, K_2O, P_2O_5, SrO, BaO, and Mn_3O_4 were present. About two percent of the Wellman-Galusha cyclone dust oxide content was undetermined.

Proximate/Ultimate Analysis of Cyclone Dusts--Proximate/ultimate analyses were performed on all ten cyclone dusts. These data are given in Table D-5 in the appendices. Summary ranges for these data are given in Table 9. Ranges of each component are given along with the identity of the facility test associated with the lowest and highest values for each parameter. These data show the following trends:

- Chapman facility cyclone dust had the highest carbon content;
- KRW-Pittsburgh #8 cyclone dust had the highest Btu value and the highest fixed carbon, hydrogen, oxygen and sulfur content;
- Wellman-Galusha (Glen-Gery) cyclone dust had the highest percent fixed carbon;
- Texaco cyclone dust had the highest ash content (ultimate);
- Lurgi-type (Kosovo) cyclone dust had the highest moisture content; and
- Texaco (Ruhrchemie) scrubber fines had the highest percent ash (proximate) and the highest chlorine content.

Proximate/ultimate analyses of cyclone dusts generally had high heating values indicating that recycle or use as a combustion fuel may be a viable alternative to disposal. Compared to the gasifier ashes, the cyclone dusts were generally lower in ash content, equivalent in sulfur and chlorine content, and higher in percent carbon, hydrogen, nitrogen, and oxygen.

Radioactive Species Analysis--For the Wellman-Galusha (Fort Snelling) and Riley facilities, fifteen radioactive species were measured. These data are given in Table D-6 in the appendices. Radioactive species present in the two cyclone dusts with activities greater than one pico Curie per gram

TABLE 9. RANGES OF RESULTS FROM PROXIMATE/ULTIMATE ANALYSIS OF GASIFIER CYCLONE DUSTS

Analysis	Facilities[a] Comparative Values High	Low	Range
PROXIMATE			
Moisture (%)	F	B	0.44-24
Ash (%)	G	F	15-75.48
Volatile (%)	F	H	1.6-35
Fixed Carbon (%)	H	G	20.77-77.6
ULTIMATE			
Btu/1b (Kcal/Kg)	H	G	3,472->10,900 (1929->6056)
Carbon (%)	A	G	18.72-92.42
Hydrogen (%)	F	G	0.21-4
Nitrogen (%)	F	I	0.45-21
Chlorine (%)	G	D	0-0.05
Sulfur (%)	H	I	0.48-2.3
Ash (%)	G	B	18.89-79.56
Oxygen (%)	B	E	0-9.02

[a] Code used in this table to identify source test:
- A Chapman
- B Wellman-Galusha (Ft. Snelling)
- C Wellman-Galusha (Glen-Gery)
- D Riley
- E Foster-Wheeler/STOIC
- F Lurgi-type (Kosovo)
- G Texaco
- H KRW-Pittsburgh #8
- I KRW-WY Subbituminous

(pCi/g) included pollonium-210, radium-226, potassium-40, lead-214, and bismuth-214. Gross alpha ranged from 8.4 pCi/g (Wellman-Galusha at Glen-Gery) up to 81 pCi/g (Texaco-Ruhrchemie). Gross beta ranged from less than detection limits for Wellman-Galusha (Fort Snelling) and Riley up to 67 pCi/g for the Texaco (Ruhrchemie) scrubber fines. The radioactive species identified in the cyclone dusts differed from the species found in the gasifier ashes.

For the KRW-Pittsburgh #8 and KRW-ND lignite cyclone dusts polonium-210 and radium-226 were determined to be below 2 pCi/g. Gross alpha and gross beta were determined for KRW-WY subbituminous, Pittsburgh #8, and ND lignite cyclone dusts. The gross alpha concentration ranged from 23 pCi/g (WY subbituminous) down to <9.5 pCi/g (ND lignite). The gross beta values ranged from 35 pCi/g (WY subbituminous) to 19 pCi/g (Pittsburgh #8).

Gas Chromatographic-Mass Spectrographic Analysis--Cyclone dusts from Wellman-Galusha (Glen-Gery), Riley, Foster Wheeler/STOIC, and Texaco (Ruhrchemie) were analyzed for base-neutral extractable compounds, acid extractable compounds, and synfuel compounds. These data are given in Table D-7 in the appendices. Under the priority pollutant category "Appendix A Base/Neutral Extractable Compounds," the following organic compounds were present:

- Acenaphthylene--Riley cyclone dust;
- Anthracene--Wellman-Galusha (Glen-Gery) cyclone dust;
- Benzidene--Wellman-Galusha (Glen-Gery) cyclone dust;
- Benzo (d) pyrene--Wellman-Galusha (Glen-Gery) and Riley cyclone dusts;
- 3,4-Benzofluoranthene--Wellman-Galusha (Glen-Gery) cyclone dust;

- Benzo (g,h,i) perylene--Wellman-Galusha (Glen-Gery) cyclone dust;
- Benzo (k) fluoranthene--Wellman-Galusha (Glen-Gery) cyclone dust;
- Bis (2-chloroethoxy) methane--Wellman-Galusha (Glen-Gery) cyclone dust;
- Bis (2-chloroethyl) ether--Wellman-Galusha (Glen-Gery) cyclone dust;
- Bis (2-chloroisopropyl)--Wellman-Galusha (Glen-Gery) cyclone dust;
- Bis (2-ethylhexyl) phthalate--Wellman-Galusha (Glen-Gery) cyclone dust and Texaco (Ruhrchemie) scrubber fines (this compound may be an artifact of sample handling);
- Chrysene--Riley cyclone dust;
- Diethyl phthalate--Wellman-Galusha (Glen-Gery) and Riley cyclone dusts (possible artifact);
- Dimethyl phthalate--Wellman-Galusha (Glen-Gery) cyclone dust (possible artifact);
- Di-n-butyl phthalate--Wellman-Galusha (Glen-Gery) cyclone dust (possible artifact);
- Fluoranthene--Riley cyclone dust;
- Fluorene--Wellman-Galusha (Glen-Gery) cyclone dust;

- Naphthalene--Wellman-Galusha (Glen-Gery), Riley and Foster Wheeler/STOIC cyclone dusts;

- 1-Methylnaphthalene--Foster Wheeler/STOIC cyclone dust;

- 2-Methylnaphthalene--Foster Wheeler/STOIC cyclone dust;

- Dimethylnaphthalene--Foster Wheeler/STOIC cyclone dust;

- Phenanthrene--Riley cyclone dust; and

- Pyrene--Riley and Foster Wheeler/STOIC cyclone dusts.

In the "Appendix A Acid Extractable Compounds," only two organic compounds were detected. In Texaco (Ruhrchemie), 2-nitrophenol was detected; however, interferences made GC/MS identification questionable. Phenol was detected in Riley cyclone dust.

In the "Appendix C Extractable Compounds," the only group of organic compounds detected were n-alkanes (C_{10}-C_{30}) for Texaco (Ruhrchemie) cyclone dust.

Of the synfuel compounds, hexanoic acid was detected in Texaco (Ruhrchemie) scrubber fines.

All other organic compounds listed in Table D-7 were undetected in the gasifier cyclone dusts. More priority pollutants were present in the cyclone dusts than in the gasifier ashes. Almost all of the compounds in cyclone dust, but not identified in the slag fell under the category of Base/Neutral extractable compounds. Many of these compounds might be destroyed with higher temperature or longer residence time to break down hydrocarbons.

Physical Properties Determinations

Physical properties reported for cyclone dusts studied in the source test programs are shown in Table D-8 in the appendices. Physical properties data were sparse for the cyclone dusts. Bulk densities and particle size distributions were similar to those of conventional fly ashes.

Bulk densities were measured for two samples of scrubber fines from the Texaco (Ruhrchemie) test. Compacted bulk densities (24.3 and 30.7 lb/ft^3 or 0.18 and 0.22 g/m^3) of the material were higher than uncompacted densities (18 and 22 lb/ft^3 or 0.13 and 0.16 g/m^3). The apparent specific gravity was between 2.1 and 2.2.

The ash fusion temperatures were also measured for two samples of Texaco (Ruhrchemie) scrubber fines. The initial deformation temperature was 2065°F (1129°C), with softening from 2060 to 2140°F (1127 to 1171°C) in a reducing atmosphere. The cyclone dust became fluid at 2200°F (1204°C).

Particle size determination data were available for cyclone dusts from the Wellman-Galusha (Glen-Gery), Riley, and Texaco (Ruhrchemie) tests. These dusts were determined to contain fine materials primarily below 150 um size.

RCRA Leaching

Extraction using the RCRA EP was performed on six cyclone dusts (not on Lurgi-type. Metals concentrations in cyclone dust extracts are given in Table D-9 in the appendices. All EP extracts contained permissible metals concentrations.

For Wellman-Galusha (Fort Snelling), Wellman-Galusha (Glen-Gery), Riley, and Texaco (Ruhrchemie) tests, cyclone dust RCRA EP extracts were also analyzed for unregulated elements. Analytical results from these determinations are given in Table D-10 in the appendices. Summary ranges of elemental concentrations in the RCRA EP extracts of four gasifier cyclone dusts are given in Table 10. The following observations are made from the summary data:

- Wellman-Galusha (Fort Snelling) RCRA EP extract from cyclone dust contained the highest concentrations of arsenic, barium, calcium, magnesium, potassium, selenium, and silcon;
- Wellman-Galusha (Glen-Gery) RCRA EP extract from cyclone dust contained the highest concentrations of antimony, beryllium, cobalt, copper, iron, lead, lithium, manganese, silver, and titanium;
- Riley RCRA EP extract from cyclone dust contained the highest concentrations of aluminum, chromium, molybdenum, sodium, strontium, and vanadium;
- Texaco (Ruhrchemie) RCRA EP extract from scrubber fines contained the highest concentrations of cadmium, nickel and zinc.

Some water quality parameters were measured for the RCRA EP extract of cyclone dusts from Wellman Galusha (Fort Snelling) and Texaco (Ruhrchemie) gasifiers. These data are given in Table D-11 in the appendices.

ASTM Extracts of Cyclone Dust--

The Riley and the Texaco (Ruhrchemie) gasifier cyclone dusts/fines were extracted using the ASTM extraction procedure (17). The Riley ASTM extract was analyzed for inorganic elements; the Texaco (Ruhrchemie) ASTM extract was analyzed for water quality parameters. These data are given respectively in Table D-12 and Table D-13 in the appendices.

TABLE 10. SUMMARY RANGES OF ELEMENTS IN RCRA EP EXTRACTS FROM GASIFIER CYCLONE DUSTS (mg/L)

Elements	Facilities[a] High	Facilities[a] Low	Range	RCRA Limit
Aluminum	C	A	>1-10	
Antimony	B	D	<0.005-0.03	
Arsenic	A	D	<0.003-0.02	5
Barium	A	D	0.009-1	100
Beryllium	B	C	<0.002-0.003	
Cadmium	D	C	<0.0005-0.091	1
Calcium	A	B	>10-MC[b]	
Chromium	C	D	<0.001-0.065	5
Cobalt	B	A	0.02-0.3	
Copper	B	D	<0.001-0.09	
Iron	B	C	0.024-1	
Lead	B	C	<0.002-0.7	5
Lithium	B	C	0.009-0.5	
Magnesium	A	D	1.6-MC	
Manganese	B	C	0.010->10	
Mercury	-[c]	-	<0.0005-<0.005	0.2
Molybdenum	C	A	0.002-0.11	
Nickel	D	A	0.01-0.37	
Potassium	A	D	0.82-MC	
Selenium	A	D	<0.004-0.006	1
Silicon	A	C	0.24-MC	
Silver	B	C	<0.0005-0.002	5
Sodium	C	D	0.82-230	
Strontium	C	A	1->10	
Titanium	B	D	<0.005-0.2	
Vanadium	C	A	<0.001-0.10	
Zinc	D	C	0.019-15	

[a] Code used in this table to identify source test:
A Wellman-Galusha (Fort Snelling)
B Wellman-Galusha (Glen-Gery)
C Riley
D Texaco

[b] MC = Major component.

[c] Dashes mean all reported results were below the detection limit.

Percent Soluble Elements--

The percent soluble elements in the RCRA and ASTM extracts of cyclone dusts were calculated for the EPA source test programs (1-7) as data were available. The following statements summarize these calculated values:

- For Wellman-Galusha (Fort Snelling) cyclone dust, the elements soluble in the RCRA EP at greater than one percent of the dust content were: cobalt (8%), lithium (13%), manganese (9%), nickel (7%), strontium (2%), and zinc (9%).

- For Wellman-Galusha (Glen-Gery) cyclone dust, the elements soluble in the RCRA EP at greater than one percent of dust content were: aluminum (<4%), antimony (11%), barium (1%), beryllium (2%), cadmium (5%), calcium (20%), cobalt (60%), copper (3%), iron (<2%), lead (6%), lithium (6%), magnesium (14%), manganese (35%), molybdenum (2%), potassium (20%), silicon (<4%), sodium (8%), and zinc (20%).

- For Texaco (Ruhrchemie) scrubber fines, the elements soluble in the RCRA EP at greater than one percent of the fines content were: cadmium (14%), calcium (4%), cobalt (3%), iron (8%), nickel (6%), silver (3%), and zinc (17%).

- For Riley cyclone dust the elements soluble in the RCRA EP extract at greater than one percent of the dust content were: aluminum (<20%), antimony (5%), cadmium (10%), calcium (100%), cobalt (36%), copper (8%), lithium (2%), magnesium (8%), molybdenum (55%), nickel (33%), potassium (20%), silver (10%), sodium (<100%), strontium (20%) and vanadium (7%); in the ASTM EP extract greater than one percent included aluminum (26%), beryllium (1.1%), selenium (17%), silver (8%), strontium (<92%), and vanadium (1.2%).

- For the Chapman and Foster-Wheeler/STOIC gasifiers, only selected RCRA metals were analyzed in the EP extracts of the cyclone dusts. The Chapman RCRA EP had arsenic (<100%) and barium (100%) soluble at greater than one percent of the dust content. The STOIC RCRA EP had arsenic (6%), barium (4%), chromium (100%), and lead (100%) soluble at greater than one percent of the dust content.

Although most studies have shown cyclone dusts to be non-hazardous by RCRA EP criteria, some parameters exceed permissible limits in the Riley cyclone dust. Elements appeared to be slightly more soluble from cyclone dust than from the slag. According to the calculated percent soluble levels, up to 100 percent of certain elements appear soluble. However, comparisons of RCRA data using AAS and solids data by SSMS may introduce a sizeable error.

Bioassay results showed the cyclone dust to generally have higher toxicity levels than gasifier ash.

GASIFIER TARS

Elemental analyses of three gasifier tars were reported in the EPA source test and evaluation studies (1,4,5). Proximate/ultimate analyses of three ashes from tars were also performed. Other analyses performed for the gasifier tars included polynuclear aromatic compound determinations, phenol measurements, and bioassay assessment.

Chemical Analysis of Gasifier Tars and Oils

Few gasifier tars were available and the extent of characterization was limited in the EPA source testing programs. Higher levels of metals (arsenic, chromium, lead, and mercury) were present in some of the tars analyzed by SSMS and ICPES than the limited AAS data.

Spark source mass spectrographic (SSMS) analysis was performed on tars and oils from the tests at Chapman, Riley, and Foster Wheeler/STOIC facilities (1,4,5). Elemental analysis of by-product tars and oils was available from Lurgi (SASOL I) (15). Atomic absorption analysis on Lurgi-type (Kosovo) gasifier tar was also available (6). Proximate/ultimate analysis of gasifier tars was available from the Chapman, Riley, and Lurgi-type (Kosovo) facilities (1,4,6). An array of organic analyses were performed on by-product tars in the source testing evaluation studies: infrared spectral compositions (1,6), polynuclear aromatic compounds (6), volatile organics (19), tar viscosity, specific gravity, and bioassay information (6). Summary data are presented by analytical technique in the remainder of this section.

SSMS--

Analytical data for three processes are given in Table E-1 in the appendices. A summary of these data is given in Table 11. Concentration ranges of each element are given along with the identity of the process or facility associated with the lowest and highest concentrations of each element. The following observations can be made from these limited data:

- Chapman gasifier tar had the highest concentrations of antimony, barium, bismuth, boron, chromium, copper, fluorine, gallium, iodine, lanthanum, lead, magnesium, potassium, rubidium, strontium, sulfur, and vanadium;

- Riley gasifier tar had the highest concentrations of arsenic, germanium, lithium, molybdenum, silicon, and sodium; and

- Foster-Wheeler/STOIC gasifier tar had the highest concentrations of aluminum, calcium, cesium, iron, manganese, nickel, phosphorous, tin, titanium, and zinc.

TABLE 11. SUMMARY RANGES OF ELEMENTS IN GASIFIER TARS BY SSMS ANALYSIS[a]

Element	Comparative Values		Ranges (mg/Kg tar)
	High	Low	
Aluminum	A	B	0.5->5
Antimony	C	A	<0.01-80
Arsenic	B	C	<0.2-2
Barium	C	B	1-50
Bismuth	C	A	0.03-5
Boron	C	A	0.02-1
Bromine	--[b]	--	All 0.1
Cadmium	--	--	<6 Chapman
Calacium	A	B	6-12
Cerium	--	--	5 (Chapman)
Cesium	A	B	0.02-1
Chlorine	--	--	All 0.3
Chromium	C	B	0.03-50
Cobalt	--	--	All <0.1
Copper	C	A	0.07-300
Fluorine	C	B	1-20
Gallium	C	B	0.04-<9
Germanium	B	A	<0.02-0.06
Iodine	C	B	0.02-5
Iron	A	B	0.9- MC[c]
Lanthanum	C	A	0.05-5
Lead	C	B	0.2-50
Lithium	B	A	0.03-0.04
Magnesium	C	B	0.2-2,000
Manganese	A	B	0.02-6
Molybdenum	B	A	0.02-0.1
Nickel	A	B	0.08-0.09
Phosphorous	A	B	0.8-3
Potassium	C	A	3-3000

(Continued)

TABLE 11. (Continued)

Element	Comparative Values High	Comparative Values Low	Ranges (mg/Kg tar)
Rubidium	C	B	0.01-0.5
Scandium	--	--	ND[d]
Selenium	--	--	All <0.03
Silicon	B	A	4-MC
Silver	--	--	All 0.2
Sodium	B	A	2-MC
Strontium	C	B	0.1-20
Sulfur	C	B	7-2.000
Tin	A	B	<0.02-0.04
Titanium	A	B	0.3-0.6
Vanadium	C	B	<0.01-1
Zinc	A	B	2-MC

a Code used in this table to identify source test:
A Foster-Wheeler/STOIC
B Riley
C Chapman
b Data did not allow comparison, see Table C-1.
c MC = Major component.
d ND = Not detected.

Table E-2 in the appendices lists elemental concentrations in medium heavy tar, heavy tar, bulk heavy tar, recycle tar and two light tars from Lurgi (SASOL I) and three KRW separator pit sludges as measured by ICPES. Analytical data from gasifier tars from source test evaluation studies did not include ICPES determinations.

AAS--

Sixteen elements in Lurgi-type (Kosovo) light tar were quantified using atomic absorption. Results are given in Table E-3 in the appendices. Elemental concentrations of arsenic, chromium, copper, nickel, lead, selenium, strontium, and zinc were greater than 1 mg/L in the Kosovo gasifier tar.

Proximate/Ultimate Analysis--

Proximate/ultimate analyses of gasifier by-product tars are given in Table E-5 in the appendices for the Chapman, Riley, Lurgi-type (Kosovo), and KRW facilities. The following observations can be made from these data:

- Chapman gasifier ash had the highest nitrogen and sulfur content;
- Riley gasifier ash had the highest hydrogen and oxygen content;
- Lurgi-type (Kosovo) gasifier ash had the highest carbon, hydrogen, and moisture content; and
- KRW-ND lignite ash had the highest ash sulfur content; KRW-Pittsburgh #8 had the highest fixed carbon; and KRW-WY subbituminous the highest moisture content.

Proximate/ultimate analyses of the gasifier by-product tars indicate high heating values which may encourage use of these wastes as a combustion fuel rather than codisposal with other solid wastes. High carbon and volatiles may indicate a possibility of a hazardous waste classification according to the ignitability characteristic. However, metals could be an environmental concern with incineration.

Organic Analysis of Gasifier Tar--

All of the organic compound results confirm that gasifier tars are primarily organic in nature and the organic constituents may pose a greater problem than the metals content. Polycyclic aromatic hydrocarbons, carcinogenic compounds, and toxic compounds have been identified in some of the tar samples. Organic analyses of gasifier tars included data from liquid chromatographic fraction analysis for aliphatic, aromatic, and heterocyclic compounds; phenols; amines; carboxylic acids; and alkyl halide groups. A summary of these fractions with respect to the total organic mass of each extract is given in Table 12 for the Chapman by-product tar. Concentrations are compared by intensity per gram of extract for a kilogram of tar.

Functional groups in Chapman tar from a fixed-bed coal gasifier are also summarized in Table 12. Substituted aromatic hydrocarbons with alkyl and branched alkyl substituents, bonded OH and NH, and split acid and ester carbonyl groups were identified.

Polynuclear aromatic compounds were identified in Lurgi-type (Kosovo) light and heavy tar fractions. These data are given in Tables E-8 and E-9 in the appendices. Polynuclear aromatic compounds present in greater than 10 ug/g of tar quantities in the Kosovo gasifier tars included benz(a)-anthracene; 7, 12-dimethylbenz(a)anthracene; benzo(b)fluoranthene; benzo(a)-pyrene; 3-methylcholanthrene; and dibenz(a,h)anthracene.

Phenol speciation of the light and heavy tars from Lurgi-type (Kosovo) was accomplished by GC/FID analysis. These data are given in Tables E-10 and E-11 in the appendices. Phenol compounds identified included phenol; o-cresol; m-cresol; p-cresol; 2,6-dimethyl-phenol; 3,4-dimethylphenol; and 1-naphthol. Many of the phenolic compounds were unidentified.

TABLE 12. ORGANIC EXTRACT SUMMARY, BY-PRODUCT TAR SAMPLE FROM CHAPMAN CH_2Cl_2 EXTRACT

Fraction	LC1	LC2	LC3	LC4	LC5	LC6	LC7	LC8
Total Organics								
g/kg tar	110	39	280	100	83	310	95	89
TCO, mg	6.1	3.6	68	10	35	30	0.6	7.4
GRAV, mg	200	71	470	190	120	560	180	160
Category (Int/g/kg)[a]								
Aliphatic Hydrocarbons	100/110	10/3.5						
Aromatic Hydrocarbons		100/35						
Polycyclic Aromatic Hydrocarbons			100/280	100/33				
Heterocyclic N Compounds				100/33	10/6.8	100/76	100/48	
Heterocyclic O Compounds				100/33	10/6.8	100/76		
Heterocyclic S Compounds					100/68	100/76		
Phenols						100/76		
Amines						10/7.6	100/48	
Carboxylic Acids and their Derivatives								10/44
Alkyl Halides								10/44

[a] Int = Intensity

Physical Properties of Gasifier Tars--

Physical data for gasifier tars in the source testing and evaluation studies are quite limited. Specific gravity was determined to be 1.06 for the Lurgi-type (Kosovo) tar. Table E-12 in the appendices gives tar viscosity data at two temperatures for light, medium, and heavy tar fractions from the Lurgi (SASOL I) test (15). At 100 °F tar viscosities ranged from 12.1 centistokes (CS) (medium-heavy tar) up to 67.5 CS for the heavy tar. At 140 °F, the tar viscosities ranged from 13.6 CS (light tar) up to 27.8 CS for the medium-heavy tar.

Bioassay Tests--

Results from bioassay tests using leachate from gasifier tars and, in some cases, from as-received tars are given in Appendix E. In vitro toxicity test results of Lurgi-type (Kosovo) tars indicated low Ames Assay mutagenicity for ASTM leachate of heavy tar and high Chinese hamster ovary toxicity for tar and heavy tar with entrapped dust.

No RCRA data were available for source test tars; therefore, bioassay results were summarized in Section 4 to indicate potential environmental problems. Tars have given positive Ames test results and shown high toxicity in rats. Compared to slag and cyclone dust, bioassay results indicate that gasifier tar would pose a greater threat in the environment. Therefore, use as fuel is preferable to disposal.

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APPENDIX A

GASIFIER FLOW RATE DATA

TABLE A-1. CHAPMAN GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier[a]
Inputs:	
Coal	152
Air	385
Steam (water vapor)	80
Outputs:	
Cooled product gas	495
Gasifier ash (dry basis)	9.3
Cyclone dust	0.8
By-product tar	15

[a] Average for the two operating gasifiers.
Source: L-11077, p. 18.

TABLE A-2. WELLMAN-GALUSHA (FORT SNELLING) GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier	
	Sampling Period One	Sampling Period Two
Inputs:		
Coal	320 ± 28	250 ± 21
Air	500 ± 55	444 ± 49
Steam (water vapor)	67 ± 8.4	66 ± 8.3
Outputs:		
Dry product gas	720 ± 63	570 ± 49
Product gas moisture	130 ± 16	120 ± 15
Tar	12 ± 1.4	9.8 ± 1.1
Gasifier ash	27 ± 2.8	21 ± 2.1
Cyclone dust	3.8 ± 1.3	—
Gasifier ash sluice water	~7	~7
Cyclone dust quench water	<7	

Source: L-14134, pp. A14-A16.

TABLE A-3. WELLMAN-GALUSHA (GLEN-GERY) STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier
Inputs:	
Coal	219
Air	992
Steam (water vapor)	194
Outputs:	
Product gas	1,333
Gasifier ash	20.6
Cyclone dust	0.2
Coal hopper gas	2.2
Pokehole gas	1.7

Source: L-13381, p. 30.

TABLE A-4. RILEY GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier
Inputs:	
Coal (including moisture)	1,000 ± 109
Air	1,200 ± 240
Steam	350 ± 88
Service water	2,200 ± 440
Outputs:	
Product gas (dry basis)	2,300 ± 230
Moisture in gas	620 ± 61
Gasifier ash	75 ± 30
Cyclone dust	4 ± 1
Tars and oils	21 ± 4
Ash pan water	2,200 ± 440

Source: L-21504, p. 14.

TABLE A-5. FOSTER-WHEELER/STOIC GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier
Inputs:	
Coal (including moisture)	300 ± 30
Air	620 ± 120
Steam (water vapor)	70 ± 7
Ash pan makeup water	7 ± 4
Lock hopper purge steam	16 ± 4
Pokehole purge steam	6 ± 2
Outputs:	
Combined product gas (dry basis)	930 ± 190
Moisture in product gas	75 ± 15
Gasifier ash	35 ± 4
Moisture in gasifier ash	9 ± 0.9
Cyclone dust	0.2 ± 0.1
ESP oil	4 ± 1

Source: L-21506, p. 49.

TABLE A-6. LURGI-TYPE GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier
COAL PREPARATION	
Run-of-mine coal	6,667
Dryer offgas (dry basis)	22
Dryer condensate	-
Dried coal	4,444
GASIFICATION/GAS QUENCH	
Dried coal	4,444
Oxygen	778
Steam	3,611
High pressure coal lock vent (dry basis)	65
Low pressure coal lock vent (dry basis)	5.6
Ash lock cyclone vent (dry basis)	12.4
Wet ash	750
Ash quench wastewater	720
Crude gas (dry basis)	4,675
RECTISOL AGR	
Crude gas (dry basis)	4,675
Clean product gas (dry basis)	1,275
H_2S-rich offgas (dry basis)	1,758
CO_2-rich offgas (dry basis)	1,725
Cyanic water	172
Naphtha	36
GAS LIQUOR SEPARATION	
Cyanic water	172
Heavy tar	28
Waste gas (dry basis)	12.4
Medium oil	69
Light tar	111
Phenolic water	3,611
PHENOSOLVAN/STRIPPING	
Phenolic water	3,611
Crude phenol	25
NH_3 stripper vent gas	96.5

Source: L-19173, Appendices A and C.

TABLE A-7. KRW PDU GASIFIER STREAM FLOW DATA

	Flow Rate, g/s-gasifier		
Stream	Test 1 Wyoming Subbituminous	Test 2 Pittsburgh No. 8	Test 3 North Dakota Lignite
Inputs			
Coal	219.2	141.0	271.6
Steam	56.8	73.4	67.2
Oxygen	112.8	145.3	135.6
CO_2 to gasifier	50.8	65.7	49.2
H_2O injection	0.0	150.3	0.0
Coal lockhopper gas (CO_2)	4.0	2.6	5.0
Ash lockhopper gas (CO_2)	1.7	1.7	1.7
Makeup water	479.4	207.9	161.3
Outputs			
Scrubbed and cooled product gas	364.0	321.9	453.8
Gasifier ash	11.6	16.0	15.6
Wastewater	506.1	408.1	202.4
Sludge	51.8	13.8	37.7
Coal lockhopper vent	3.5	2.3	4.2
Ash lockhopper vent	1.7	1.7	1.7

Source: L-23404, pp. 4-17, 4-19, 4-21.

TABLE A-8. KOPPERS-TOTZEK GASIFIER STREAM FLOW RATE DATA

Stream	Flow Rate, g/s-gasifier
Inputs:	
Pulverized coal	1,750
Oxygen	1,640
Steam	175
Outputs:	
Raw gas (dry)	3,110
Slag	80
Discharge water	2,275
Fly ash (dry)	210

Source: L-19349.

TABLE A-9. TEXACO GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier Period One[a]	 Period Two[b]
Inputs:		
Coal (dry basis)	1,690	1,634
Oxygen	1,564	1,561
Fresh water[c]	1,319	347
Demineralized water	1,424	1,278
Outputs:		
Scrubbed synthesis gas	3,221	3,206
Slag	570	501
Flash gas	7.5	8.3
Settler underflow-blowdown	2,141	1,029

[a] No recycle of clarifier underflow.
[b] Minimization of fresh water makeup by recycle of clarifier underflow.
[c] Includes water in coal feed, additive mixture, and flocculant mixture.
Source: L-21461, pp. 4-8, 4-9.

APPENDIX B

INTERNAL QUALITY CONTROL

The data compiled in this summary report originated from a series of Source Test and Evaluation projects conducted over a period of several years. During this time span the measurement techniques and quality control requirements were modified and evolved such that no single consistent set characterizes all of the data. The quality control procedures described below are generally applicable to these data types.

The internal quality control (QC) system for these data provided a set of routine internal procedures for assuring that the data output met prescribed criteria for data quality. Inherent and implied in this control function was a parallel function of measuring and defining the quality of the data output. A well-designed internal QC program must be capable of controlling and measuring the quality of the data, in terms of precision and accuracy. Precision reflects the influence of the inherent variability in any measurement system. Accuracy reflects the degree to which the measured value represents the actual or "true" value for a given parameter, and includes elements of both bias and precision. Accuracy of measurement data is related to the precision and bias of the component parts of the measurement system.

Generally, the internal QC procedures may be divided into two overlapping categories. One category includes those procedures which were used to control data quality within the prescribed limits of acceptability.

These acceptability limits are usually related to data precision, accuracy, and completeness. The other category includes those procedures designed to provide a quantitative assessment of data quality, again in terms of precision, accuracy, and completeness. Some internal QC procedures, by their nature, fall into both categories.

PROCEDURES USED FOR CONTROL AND ASSESSMENT OF DATA QUALITY

Those procedures which served both control and assessment functions first come to mind when quality control is mentioned. Examples include:

- replicate and repeat analyses (split samples),
- blank analyses,
- replicate samples,
- control samples,
- drift checks,
- spiked samples, and
- QA audits.

Procedures of this type were performed at a specified frequency, with a requirement that specific acceptance criteria be met prior to proceeding with sample analyses. Failure to meet prescribed acceptance criteria indicated the need for corrective action. By selecting appropriate acceptance criteria for QC results, the quality of the measurement data was effectively controlled within predetermined limits. Since precision and accuracy are most frequently the quality aspects which were being controlled, acceptance criteria for these types of procedures were defined in terms related to precision and accuracy. An essential part of the control function is the requirement that all acceptance criteria be met prior to proceeding with actual sample analyses. Table B-1 is an example of a summary of internal QC requirements for the testing programs which includes designated frequencies and specific acceptance criteria for each procedure.

In addition to controlling data quality within prescribed limits, the QC data provided the basis for assessing the performance of the measurement system. This assessment, usually involving statistical treatment of the QC data, was used to define various aspects of measurement data quality, including precision and accuracy. One major advantage of the types of procedures listed above is the ongoing nature of this assessment which represents a powerful feedback mechanism in a corrective action scheme. In order to maximize this potential, the data should be plotted and/or tabulated on a routine basis. Control charts are often used for this purpose, with some variation of the Shewhart chart being the most popular type of control chart.

ADDITIONAL DATA QUALITY ASSESSMENT PROCEDURES

In addition to the QC checks described above, which provided both ongoing assessment and control of the measurement system, other QC procedures were used in what is, practically speaking, strictly an assessment function. Any control benefits of these types of QC procedures are realized only over the long term, as through modification or refinement of procedures and techniques. Examples of these evaluative procedures include:

- collaborative tests,
- methods validation studies,
- interlaboratory (round-robin) analyses,

TABLE B-1. SUMMARY OF INTERNAL QUALITY CONTROL PROCEDURES FOR SOLIDS AND LIQUID HYDROCARBON SAMPLES

Parameter	Analytical Method	Quality Control Check	Frequency	Acceptance Criteria	Action or Corrective Action
Sulfate, Pyritic, and Organic Sulfur*	ASTM-D-2492-84	Performed by contract laboratory	Will rely on contract lab QA/QC procedures		
		Duplicate analyses	One blind duplicate will be submitted.		
Extractable Organics*	Gravimetric	Methylene chloride blank	Prior to sample analyses	None	Used to indicate level of analytical contamination
		Duplicate analyses	10% (minimum 1)	None	Report results
As, Hg, Pb, Sb, Se	Atomic Absorption	Calibration blank	Prior to sample analyses	Blank less than two times detection limit	Repeat analysis
		Digestion blank	Prior to analyses	Less than three times element detection limit	Determine source of contamination and redigest
		Control sample	1) Immediately following calibration 2) 10% (minimum 2) thereafter	Measured value within ± 15% of true value	1) Repeat analysis 2) Repeat calibration
As, Hg, Pb, Sb, Se		Mid-level standard	1 in 20 if more than 20 samples analyzed	Response within ±10% of original calibration curve	Repeat calibration
		Duplicate digestion and analysis	10% (minimum 1)	Relative percent difference (RPD) ≤20% for replicate determinations for quantitations greater than five times detection limit	Repeat duplicate analyses
		Sample spikes	10% (minimum 1)	Spike recovery between 80-120%	Repeat spike analysis
Ag, B, Be, Cd, Cr, Cu, Ni, Ti, Zn	EPA/200.7	Instrument check standard	10% (minimum 1)	Measured value within ±5% of true value for elements of interest (±10% for Ag)	Repeat calibration

*Solids only.

(continued)

TABLE B-1 (Cont.)

Parameter	Analytical Method	Quality Control Check	Frequency	Acceptance Criteria	Action or Corrective Action
Ag, B, Be, Cd, Cr, Cu, Ni, Ti, Zn (continued)	EPA/200.7	Calibration blank	10% (minimum 1)	Results within 2 standard deviations of mean for elements of interest	Repeat analysis (average 3 analyses)
		Interference check sample	10% (minimum 1)	Results within 1.5 times standard deviation of mean for elements of interest	Repeat calibration
		Sample spikes	10% (minimum 1)	Spike recovery between 80-120% for elements of interest	Repeat spike analysis
		Duplicate analysis	10% (minimum 1)	Analyses agreement within 20% relative percent difference (RPD) for concentrations five times greater than detection limits	Repeat duplicate analysis
		Digestion blank analysis	Prior to sample analyses	Less than three times detection limit	Determine source of contamination and redigest

- analysis of variance studies, and

- method comparisons.

These types of QC procedures were not included in the day-to-day QC system, but rather were used for specific applications. They are especially suited to projects which involve methods development or which require modification of standard methods for a particular novel measurement application or situation.

ADDITIONAL DATA QUALITY CONTROL PROCEDURES

The QC procedures described above are oriented to quantitative data QC in the sense that there is an obvious and direct link between each procedure and some measureable aspect of data quality. Another type of QC procedures served a control function which was more qualitative rather than quantitative. Strict adherence to prescribed measurement procedures falls into this category, and is often the single most important QC procedure in terms of overall impact on measurement data quality. Other examples of this type of QC procedure include:

- training of personnel,

- preventive maintenance,

- documentation,

- calibration/standardization procedures,

- data review and calculation checks,

- use of formatted data forms which serve as checklists,

- careful consideration in experimental design,
- data reduction procedures, and
- statistical data evaluation.

APPENDIX C

DATA COMPILATION FOR GASIFIER ASHES

TABLE C-1. SUMMARY OF SPARK SOURCE MASS SPECTROGRAPHIC ANALYSES OF GASIFIER ASHES (mg/Kg ash)

Element	Chapman	Wellman-Galusha (Fort Snelling)	Wellman-Galusha (Glen-Gery)	Riley	Foster Wheeler/ STOIC	Lurgi-Type (Kosovo)	Texaco (Ruhrchemie)
Aluminum	MC[a]	MC	3,020	>1000	<1000	MC	>1000
Antimony	3	1	200	0.5	2	2	1
Arsenic	9	38	<0.4	3	62	9	1
Barium	760	MC	2000	>1000	<1000	MC	>1000
Beryllium	0.7	0.3	10	1	4	9	0.9
Bismuth	0.3	NR[b]	NR	18	NR	NR	<0.1
Boron	66	76	20	13	190	320	64
Bromine	4	3	NR	6	17	2	3
Cadmium	0.3	NR	<9	0.4	NR	0.8	5
Calcium	MC	MC	50000	>1000	>1000	MC	>1000
Cerium	140	47	90	180	29	110	59
Cesium	12	2	NR	10	3	8	8
Chlorine	130	45	NR	8	45	34	10
Chromium	450	21	30	190	2	100	8
Cobalt	54	1	50	23	4	23	1
Copper	79	2	1000	200	27	81	23
Dysprosium	7	2	NR	3	2	7	6
Erbium	16	0.7	NR	1	9	3	3
Europium	4	1	NR	1	1	3	1
Fluorine	270	160	<200	59	720	190	110
Gadolinium	8	2	NR	2	2	4	4
Gallium	26	15	50	22	17	9	23
Germanium	8	4	NR	1	0.5	1	0.7
Gold	ND[c]	NR	NR	NR	NR	NR	ND
Hafnium	4	<2	NR	2	NR	1	2
Holmium	3	1	NR	2	0.6	4	4
Iodine	2	0.4	NR	0.3	2	0.2	0.3
Iridium	ND	NR	NR	NR	NR	NR	ND
Iron	MC	MC	1000	>1000	>1000	MC	>1000
Lanthanum	150	47	100	160	21	110	180
Lead	21	8	20	12	9	5	12
Lithium	25	6	70	>240	28	48	64
Lutetium	0.4	NR	NR	0.3	NR	0.3	0.3
Magnesium	MC	MC	6,000	>1000	>1000	MC	>1000
Manganese	MC	230	NR	69	>1000	170	230
Molybdenum	39	5	NR	0.28	6	15	3
Neodymium	49	9	NR	15	10	30	19
Nickel	160	7	NR	34	180	75	3
Niobium	36	37	20	62	10	31	38
Osmium	ND	NR	NR	35	NR	NR	ND
Palladium	ND	NR	NR	NR	NR	NR	ND
Phosphorus	MC	MC	800	>1000	>1000	MC	>1000
Platinum	ND	NR	NR	ND	NR	NR	NR
Potassium	MC	MC	10000	>1000	>1000	MC	>1000

(Continued)

TABLE C-1. (Cont.)

Element	Chapman	Wellman-Galusha (Fort Snelling)	Wellman-Galusha (Glen-Gery)	Riley	Foster Wheeler/ STOIC	Lurgi-Type (Kosovo)	Texaco (Ruhrchemie)
Praseodymium	31	4	NR	16	5	16	16
Rhenium	ND	NR	NR	<0.1	NR	NR	ND
Rhodium	ND	NR	NR	NR	NR	NR	ND
Rubidium	100	16	2000	150	35	47	59
Ruthenium	ND	NR	NR	NR	NR	NR	ND
Samarium	16	5	NR	11	9	13	6
Scandium	46	11	50	9	12	20	2
Selenium	14	5	30	2	<1	4	0.8
Silicon	MC	MC	7,000	>1000	>1000	MC	>1000
Silver	0.6	3	NR	1	NR	0.6	<0.3
Sodium	MC	MC	NR	>1000	>1000	MC	<170
Strontium	710	MC	2000	490	320	MC	>1000
Sulfur	MC	MC	1000	>10000	420	MC	<420
Tantalum	1	NR	NR	NR	NR	<0.8	0.6
Tellurium	0.6	<0.3	NR	<0.2	<1	NR	0.2
Terbium	2	1		0.6	NR	1	1
Thallium	5	17	NR	0.3	NR	NR	0.4
Thorium	30	NR	NR	29	0.5	23	29
Thulium	0.6	0.2	NR	0.2	NR	0.4	0.2
Tin	3	2	300	2	0.8	0.5	0.5
Titanium	MC	MC	3000	>1000	>1000	MC	>1000
Tungsten	3	2	NR	2	NR	1	2
Uranium	62	6	400	32	2	16	19
Vanadium	270	61	30	200	67	410	68
Ytterbium	4	1	NR	2	NR	3	2
Yttrium	140	60	<20	66	17	59	50
Zinc	290	12	NR	18	33	20	2
Zirconium	150	160	90	350	33	180	200

Source: Refs. 1-7.
[a] MC = Major component.
[b] NR = Not reported.
[c] ND = None detected.

TABLE C-2. SUMMARY OF INDUCTIVELY COUPLED ARGON PLASMA EMISSION SPECTROGRAPHIC ANALYSIS OF GASIFIER ASH (mg/Kg ash)

Element	Wellman-Galusha (Fort Snelling) A Run	Wellman-Galusha (Fort Snelling) B Run	Riley	Foster Wheeler/ STOIC	Texaco (Ruhrchemie)	KRW-WY Subbituminous	KRW- Pitts. #8	KRW- ND Lignite
Aluminum	19100	18900	45000	78000	73000	86000	69000	28000
Antimony	NR[a]	NR	1	NR	<1.2	0.77	0.25	1.2
Arsenic	<100	<100	56	NR	43	41	35	46
Barium	1900	1900	3400	3300	420	1060	200	96
Boron	220	200	110	690	820	110	175	305
Cadmium	<6.2	<6.2	NR	NR	0.65	1.3	18	60
Calcium	48800	48100	96000	50000	32000	68000	29000	36000
Chromium	22	20	<0.2	42	160	70	17	82
Cobalt	<190	<190	17	12	34	30	23	120
Copper	33	47	44	32	55	80	46	40
Iron	30400	30100	56000	4%	81000	50000	61000	61000
Lead	>87	>87	NR		32	22	7.7	8.8
Magnesium	12300	12100	22000	12000	5300	14000	4400	8600
Manganese	64	64	250	440	380	125	19	2200
Molybdenum	<50	<50	23	16	45	7.9	12	16
Nickel	71	62	26	31	130	56	26	<30
Phosphorus	NR	NR	NR	NR	NR	790	3000	6400
Potassium	NR	NR	7000	8200	12000	4400	13000	8200
Silver	<6.2	<6.2	NR	NR	0.72	<0.18	NR	NR
Sodium	<6300	<6200	24000	1500	5700	5600	7400	22000
Strontium	1300	1300	NR	NR	NR	1500	670	2200
Thallium	NR	NR	NR	NR	NR	ND[b] (0.2)	ND (0.1)	ND (1)
Tin	<50	<50	NR	NR	NR	NR	NR	NR
Titanium	1200	1200	2200	1800	5200	5100	4600	2900
Uranium	NR	NR	NR	NR	NR	ND (6)	ND (6)	ND (6)
Vanadium	38	37	90	66	180	130	79	110
Zinc	25	4.6	38	15	280	380	35	32

Source: Refs. 1-8.

[a] NR - Not reported.

[b] ND - Not detected (detection limit).

TABLE C-3. SUMMARY OF ATOMIC ABSORPTION SPECTROPHOTOMETRIC ANALYSIS OF GASIFIER ASH (mg/Kg ash)

Element	Chapman	Wellman-Galusha (Fort Snelling)	Wellman-Galusha (Glen-Gery)	Riley	Foster Wheeler/ STOIC	Lurgi-Type (Kosovo)	Texaco (Ruhrchemie)
Arsenic	<0.4	30	3	56	24	75	35
Antimony	200	<0.4	0.5	0.57	<0.2	<0.2	<1.2
Beryllium	NA[a]	NA	NA	NA	NA	2.5	NA
Cadmium	NA	NA	NA	NA	NA	69	0.65
Chromium	NA	NA	NA	NA	NA	180	NA
Cobalt	NA	NA	NA	NA	NA	17	NA
Copper	NA	NA	NA	NA	NA	40	NA
Lead	NA	NA	NA	NA	NA	52	39
Mercury	<0.3	1.7	0.28	NA	0.3	0.3	6.
Molybdenum	NA	NA	NA	NA	NA	8.9	NA
Nickel	NA	NA	NA	NA	NA	320	120
Selenium	NA	15	NA	<1	0.6	24	6.9
Silver	NA	NA	NA	NA	NA	NA	0.4
Strontium	NA	NA	NA	NA	NA	370	NA
Vanadium	NA	NA	NA	NA	NA	100	NA
Zinc	NA		NA	NA	NA	21	NA

Source: Refs. 1-7.

[a] NA = Not analyzed.

TABLE C-4. SUMMARY OF ASH MINERAL ANALYSIS OF GASIFIER ASH

Component	Wellman-Galusha (Fort Snelling) (%)	Texaco (Ruhrchemie) (%)	Koppers-Totzek (Ptolemais) (%)
SiO_2	39.18	49.92	50.2
Al_2O_3	22.38	19.70	25.5[a]
TiO_2	1.02	0.85	--[a]
FeO_3	13.40	17.38	--[b]
Fe_2O_3	--	--	4.5
CaO	9.02	5.15	3.9
MgO	2.89	1.17	1.2
K_2O	1.39	2.20	2.5[c]
Na_2O	3.26	1.09	--[c]
SO_3	3.43	2.06	--
P_2O_5	0.61	0.22	0.1
SrO	0.31	0.00	--
BaO	0.83	0.04	--
Mn_3O_4	0.04	0.08	--
Undetermined	2.24	0.14	12.2
	100.00	100.00	100.0

Source: Refs. 2, 7, and 9.
[a] Reported as % Al_2O_3 + % TiO_2.
[b] Dash means no data available.
[c] Reported as % Na_2O + % K_2O.

TABLE C-5. SUMMARY OF PROXIMATE/ULTIMATE ANALYSIS OF GASIFIER ASHES

Analysis	Wellman Galusha (Fort Snelling)	Wellman Galusha (Glen Gery)	Riley	Foster Wheeler/ STOIC	Lurgi-Type (Kosovo)	Texaco (Ruhrchemie)	KRW-WY Subbituminous	KRW-Pitts. #8	KRW-ND Lignite
PROXIMATE									
Ash (%)	73.66	24.70	62.54	77.08	95	79.56	74.1	88.8	91.9
Volatile (%)	6.49	2.88	10.59	3.29	-	2.70	2.08	0.57	7.30
Fixed Carbon (%)	18.84	71.71	26.87	19.63	1.8	17.74	23.8	10.6	0.81
ULTIMATE									
Btu/lb[a]	3,709	3,193	4,993	2,984	-	3,036	3,600	960	710
Moisture		0.9					0.42	0.19	0.14
Carbon (%)	24.64	32.98	35.36	20.63	1.8	18.72	24.31	6.44	4.49
Hydrogen (%)	0.41	0.27	0.61	0.11	0.26	0.21	0.33	0.09	0.07
Nitrogen (%)	0.17	0.18	0.46	0.24	0.03	0.70	0.26	0.22	0.43
Chlorine (%)	0.02	0.01	0.003	0.00	0.04	0.05	0.03	0.04	0.01
Sulfur (%)	1.09	0.20	1.64	0.27	0.15	1.73	0.96	4.42	3.11
Ash (%)	74.41	65.81	62.54	77.08	95	79.56	74.1	88.8	91.9
Oxygen (diff)	0.06	0.30	0	1.67	2.3	-	0.0	0.0	0.0
	100.80	100.65	101.61	100.00	99.58	100.97	100.08	100.20	100.15

Source: Refs. 2-8.

[a] Btu/lb x 0.5555 = kcal/kg.

TABLE C-6. SUMMARY OF RADIOACTIVE SPECIES ANALYSIS IN GASIFIER ASHES (pCi/g)

Compound	Wellman-Galusha (Fort Snelling)	Wellman-Galusha (Glen-Gery)	Riley	Texaco (Ruhrchemie)	KRW-Pitts. #8	KRW-ND Lignite
Po-210	0.496		0.4040			
Ra-226	5.500		2.700	4.1	2.1 (0.2)[a]	2.3 (0.2)
Ra-228					2.0 (1.1)	1.5 (0.6)
U -234	4.8600		1.1830			
U -235	0.284		0.06153	ND[b]		
U -238	4.9600		1.3220			
K -40	8.8600		7.800			
Pb-214	4.330		1.700	27		
Bi-214	4.3500		1.200	22		
Th-233	2.1100		0.7300			
Th-227	0.43100		0.1684			
Th-228	2.6400		1.1410			
Th-230	5.500		1.4820			
Th-232	2.6100		1.0960	10		
Pb-210	0.539		0.5560	30		
Pb-212				2.0		
Gross (Alpha)	46	9.5	NR[c]	36	6.2 (3.0)	6 (4)
Gross (Beta)	52	0	NR	40	21 (4.6)	19 (5)

Source: Refs. 2, 3, 4, 7, and 8.

[a] The number in parentheses represents the one sigma error.

[b] ND = Not detected.

[c] NR = Not reported.

TABLE C-7. SUMMARY OF RESULTS OF GC/MS ORGANIC ANALYSIS OF GASIFIER ASHES[a]

Compound	Wellman Galusha (Glen Gery)	Riley	Foster Wheeler/ STOIC	Texaco (Ruhrchemie) Run A	Texaco (Ruhrchemie) Run B	KRW WY Sub.	KRW Pittsburgh #8	KRW ND Lignite
Appendix A Base/Neutral Extractable Compounds								
Acenaphthene	ND[b]	ND	ND	ND(0.21)	ND(0.15)	NM[c]	0.090	0.009
Acenaphthylene	ND	ND	ND	ND(0.21)	ND(0.15)	NM	ND	ND
Anthracene	ND	ND	ND	ND(0.21)	ND(0.15)	NM	ND	ND
Benzidine	ND	ND	ND	ND(0.21)	ND(0.15)			
Benzo(a)pyrene	ND	ND	ND	ND(0.21)	ND(0.15)	NM	ND	ND
3,4-Benzofluoranthene	ND	ND	ND	ND(0.21)	ND(0.15)			
Benzo(g,h,i)perylene	ND	ND	ND	ND(0.53)	ND(0.38)	NM	ND	ND
Benzo(k)fluoranthene	ND	ND	ND	ND(0.21)	ND(0.15)	NM	ND	ND
Bis(2-chloroethoxy)methane	ND	ND	ND	ND(0.21)	ND(0.15)			
Bis(2-chloroethyl)ether	ND	ND	ND	ND(0.21)	ND(0.15)			
Bis(2-chloroisopropyl)ether	ND	ND	ND	ND(0.21)	ND(0.15)			
Bis(2-ethylhexyl)phthalate	0.58	ND	0.04	170[d]	ND(0.15)			
4-Bromophenyl phenyl ether	ND	3.47	ND	ND(0.21)	ND(0.15)			
Butyl benzyl phthalate	ND	ND	ND	ND(0.21)	ND(0.15)			
2-Chloronaphthalene	ND	ND	ND	ND(0.21)	ND(0.15)			
4-Chlorophenyl phenyl ether	ND	ND	ND	ND(0.21)	ND(0.15)			
Chrysene	ND	0.25	ND	ND(0.21)	ND(0.15)	NM	ND	ND
Dibenzo(a,h)anthracene	ND	ND	ND	ND(0.53)	ND(0.38)	NM	ND	ND
1,2-Dichlorobenzene	ND	ND	ND	ND(0.21)	ND(0.15)			
1,3-Dichlorobenzene	ND	ND	ND	ND(0.21)	ND(0.15)			
1,4-Dichlorobenzene	ND	ND	ND	ND(0.21)	ND(0.15)			
3,3'-Dichlorobenzidine	ND	ND	ND	ND(0.21)	ND(0.15)			
Diethyl phthalate	0.05	0.14	ND	ND(0.21)	ND(0.15)			
Dimethyl phthalate	ND	ND	ND	ND(0.21)	ND(0.15)			
Di-n-butyl phthalate	0.08	0.11	ND	ND(0.21)	ND(0.15)			
2,4-Dinitrotoluene	ND	ND	ND	ND(0.21)	ND(0.15)			
2,6-Dinitrotoluene	ND	ND	ND	ND(0.21)	ND(0.15)			
Di-n-octyl phthalate	ND	ND	ND	ND(0.21)	ND(0.15)			
1,2-Diphenyl hydrazine (as Azobenzene)	ND	ND	ND	ND(0.21)	ND(0.15)			
Fluoranthene	ND	0.12	ND	ND(0.21)	ND(0.15)	NM	ND	ND
Fluorene	ND	ND	ND	ND(0.21)	ND(0.15)	NM	0.004	ND
Hexachlorobenzene	ND	ND	ND	ND(0.21)	ND(0.15)			
Hexachlorobutadiene	ND	ND	ND	ND(0.21)	ND(0.15)			
Hexachlorocyclopentadiene	ND	ND	ND	ND(0.21)	ND(0.15)			
Hexachloroethane	ND	ND	ND	ND(0.21)	ND(0.15)			
Indeno(1,2:c,d)pyrene	ND	ND	ND	ND(0.53)	ND(0.38)	NM	ND	ND
Isophorone	ND	ND	ND	ND(0.21)	ND(0.15)			
Naphthalene	ND	0.13	0.01	ND(0.21)	ND(0.15)	0.58	>1.6	>0.84
Nitrobenzene	ND	ND	ND	ND(0.21)	ND(0.15)			
N-Nitrosodimethylamine	ND	ND	ND	ND(1.1)	ND(0.75)			

(Continued)

TABLE C-7 (Continued)

Compound	Wellman Galusha (Glen Gery)	Riley	Foster Wheeler/ STOIC	Texaco (Ruhrchemie) Run A	Texaco (Ruhrchemie) Run B	KRW WY Sub.	KRW Pittsburgh #8	KRW ND Lignite
Appendix A Acid Extractable Compounds								
N-Nitrosodi-N-propylamine	ND	ND	ND	ND(0.21)	ND(0.15)			
N-Nitrosodiphenylamine (detected as diphenylamine)	ND	ND	ND	ND(0.21)	ND(0.15)			
Phenanthrene	ND	0.06	ND	ND(0.21)	ND(0.15)	NM	0.001	ND
Pyrene	ND	0.12	ND	ND(0.21)	ND(0.15)	NM	ND	ND
1,2,4-Trichlorobenzene	ND	ND	ND	ND(0.21)	ND(0.15)			
2-Chlorophenol	ND	ND	ND	ND(0.53)	ND(0.38)			
2,4-Dichlorophenol	ND	ND	ND	ND(0.53)	ND(0.38)			
2,4-Dimethylphenol	ND	ND	ND	ND(0.53)	ND(0.38)	NM	ND	ND
2,6-Dinitro-o-cresol	ND	ND	ND	ND(5.3)	ND(3.8)			
2,4-Dinitrophenol	ND	ND	ND	ND(0.53)	ND(0.38)			
2-Nitrophenol	ND	ND	ND	ND(0.53)	ND(0.38)			
4-Nitrophenol	ND	ND	ND	ND(0.53)	ND(0.38)			
p-Chloro-m-cresol	ND	ND	ND	ND(0.53)	ND(0.38)			
Pentachlorophenol	ND	ND	ND	ND(0.53)	ND(0.38)			
Phenol	ND	ND	ND	ND(0.53)	ND(0.38)	0.09	0.004	ND
2,4,6-Trichlorophenol	ND	ND	ND	ND	ND			
Appendix C Extractable Compounds								
n-Alkanes (C_{10}-C_{30})	ND	ND	ND	ND(0.21)	1.0			
Biphenyl	ND	ND	ND	ND(0.21)	ND(0.15)	NM[d]	0.020	0.004
Camphor	ND	ND	ND	ND(0.64)	ND(0.44)			
Cumene	ND	ND	ND	ND(0.32)	2.8			
Dibenzofuran	ND	ND	ND	ND(0.21)	ND(0.15)	NM	ND	ND
Diphenyl amine	ND	ND	ND	ND(0.64)	ND(0.44)			
Diphenyl ether	ND	ND	ND	ND(0.53)	ND(0.36)			
-Terpineol	ND	ND	ND	ND(0.53)	ND(0.36)			
Synfuels Compounds								
2-Aminonaphthalene	ND	ND	ND	ND(1.1)	ND(0.74)			
Benzoic acid	ND	ND	ND	ND(0.36)	ND(0.75)			
Benzothiophene	ND	ND	ND	ND(0.53)	ND(0.36)	NM	0.11	0.013
Hexanoic acid	ND	ND	ND	ND(0.53)	ND(0.36)			
2-Methylpyridine	ND	ND	ND	ND(0.69)	ND(0.49)			

Source: Refs. 3, 4, 5, 7, and 8.

[a] Concentrations as g/g of solid.

[b] ND( ) - Not detected (detection limit).

[c] NM - Not measured.

[d] Suspected contamination from plastic sample container.

TABLE C-8. SUMMARY OF PHYSICAL CHARACTERISTICS OF GASIFIER ASHES

Characteristic	Wellman Galusha (Glen-Gery)	Riley	Texaco (Ruhrchemie) Run A	Texaco (Ruhrchemie) Run B	KRW-WY Subbituminous	KRW-Pitts. #8	KRW-ND Lignite
Bulk Density in lb/ft^3(g/m^3)							
Compacted			57.2 (0.42)	53.2 (0.39)			
Uncompacted			43.5 (0.32)	43.8 (0.32)			
Specific Gravity							
Apparent			2.086	2.423	1.83	2.11	2.11
Ash Fusion Temperature (°F)[b]							
Initial Deformation			2080(2300)	2060(2250)			
Softening (H = W)			2090(2340)	2070(2270)			
Softening (H - 1/2W)			2095(2380)	2090(2290)			
Fluid			2120(2400)	2110(2360)			
Particle Size Determination[c]							
Particle Diameter	Weight Percent Retained						
12.5 mm	23.9						
9.5 mm	14.6						
6.3 mm	7.3						
3.35 mm					0.6	2.6	0.4
2.00 mm	26.8		14.1	9.4	5.4	17.6	6.2
1.00 mm	13.7						
850 um							
710 um	3.7		30.2	2.25	42.6	67.1	57.8
425 um			12.7	13.8			
250 um			15.4	15.7			
212 um					32.4	11.2	29.2
100 um			8.9	12.6	13.7	0.7	4.8
75 um			10.2	13.3	1.9	0.1	0.6
<75 um			8.3	12.8	3.4	0.7	1.0

Source: Refs. 3, 4, 7, and 8.

[a] All values determined for moisture-free solids.

[b] Values are for reducing atmosphere (oxidizing atmosphere). Raw coal results are for a composite of Environmental Balance Periods One and Two.

[c] Particle size determination as percent mass retained on sieve.

[d] Particle size range distribution was 14 mm to <75 mm.

TABLE C-9. SUMMARY OF ASH LEACHATE COMPOSITION FOR RCRA EXTRACTS (mg/L)

Gasifier	Arsenic	Barium	Cadmium	Chromium	Lead	Selenium	Mercury	Silver
Chapman[a]	0.010	2	<0.002	<0.003	0.01	0.01	NR[b]	<0.002
Wellman-Galusha[a] (Fort Snelling)	0.005	1	0.007	0.001	NR	0.005	NR	NR
Wellman-Galusha[a] (Glen Gery)	0.004	0.1	0.001	0.002	0.008	<0.001	NR	0.005
Riley[c]	0.033	0.68	<0.0005	<0.001	<0.002	<0.01	<0.0005	<0.0005
Foster-Wheeler/[c] STOIC	<0.003	0.65	0.1	<0.002	<0.002	<0.004	<0.0002	<0.006
Lurgi-type[a] (Kosovo)	<0.004	3	NR	0.3	NR	<0.004	NR	NR
Sasol I[c] (Tristates)	<0.002	0.13	0.0005	<0.001	<0.002	<0.003	<0.0002	<0.001
Texaco[c] (Ruhrkohle/Ruhrchemie)	<0.003	0.074	0.005	<0.001	<0.002	<0.006	<0.0005	<0.001
Koppers-Totzek[c] (Ptolemais)	<0.4	<0.01	<0.007	<0.04	<0.05	<0.4	<0.0002	<0.01
IGT U-Gas[c]	<0.002	<0.03	<0.003	0.005	0.025	<0.005	<0.0002	<0.002
RCRA Maximum Permissible Limit	5	100	1	5	5	1	0.2	5

Source: Refs. 1-7, 9, and 16.

[a] Analysis for RCRA elements done by spark source mass spectroscopy.

[b] NR = not reported.

[c] Analysis for RCRA elements done by ICPES and AA.

TABLE C-10. SUMMARY OF CHEMICAL CONCENTRATIONS OF ELEMENTS IN RCRA EP EXTRACTS FROM GASIFIER ASHES (mg/L)

Element	Chapman	Wellman-Galusha (Fort Snelling)	Wellman-Galusha (Glen-Gery)	Riley	Lurgi-type (Kosovo)	Sasol (Tristates)	Texaco (Ruhrchemie)	U-Gas IGT	KRW-WY Subbituminous	KRW-Pitts. #8	KRW-ND Lignite
Aluminum	<BC[a]	0.1	0.0006	<0.050	0.01	<0.050	0.15	NR[b]	0.06[c]	NA[d]	NA
Antimony	ND[e]	NR	NR	<.002	<0.002	<0.050	<0.005	0.0004	ND (0.03)	NA	NA
Arsenic	0.010	0.005	0.004	240/680	<0.004	<0.002	<0.003	<0.002	ND (0.003)	ND (0.003)	ND (0.003)
Barium	2.00	1	0.1	.033	3	0.13	0.019	<0.25	2.9	0.7	7.2
Beryllium	ND	NR	NR	<0.002	NA	<0.0005	<0.0005	<0.002	ND (0.0005)	NA	NA
Boron	NR	NR	NR	NR	NR	NR	NR	NR	ND (0.003)	ND (0.003)	ND (0.003)
Cadmium	ND	<0.007	0.001	<0.0005	NA	0.0005	<0.0005	<0.003	ND (0.002)	0.003[c]	ND (0.002)
Calcium	>6	MC[f]	0.099	1400	NA	190.	9.3	NR	160	NA	NA
Chromium	<0.003	0.001	0.002	0.016/<.001	0.3	<0.001	0.009	0.006	ND (0.001)	0.003[c]	0.071
Cobalt	<BC	0.007	0.001	<.006	<0.001	<0.006	3.3	NR	ND (0.006)	NA	NA
Copper	0.030	0.1	0.008	<.001	0.01	<0.001	0.079	0.05	0.045	NA	NA
Iron	5.00	2	0.01	<.008	10	0.59	0.018	0.039	0.22	NA	NA
Lead	0.010	0.007	0.008	<0.002	0.008	<0.002	<0.002	0.025	0.002[c]	ND (0.002)	ND (0.002)
Lithium	ND	0.006	0.03	.002	0.03	0.29	NA	NR	0.003	NA	NA
Magnesium	>9.96	MC	0.036	24	2	4.3	0.73	NR	16	NA	NA
Manganese	0.100	0.5	0.005	.003	0.001	0.27	0.061	0.005	0.2	NA	NA
Mercury	NA	NR	ND	<.0005	NA	<0.0002	<0.0005	<0.0002	ND (0.0002)	ND (0.0002)	ND (0.0002)
Molybdenum	<BC	0.01	0.02	0.058	0.1	<0.002	0.008	NR	ND (0.002)	NA	NA
Nickel	<BC	0.04	NR	0.02	0.04	0.015	NA	0.010	0.026	NA	NA
Phosphorus	NR	NR	NR	NR	NR	NR	NR	NR	ND (0.2)	NA	NA
Potassium	5000	MC	>6	15	NA	22.	1.4	NR	ND (0.04)	NA	NA
Selenium	0.002	0.005	<0.001	.006	0.01	<0.003	<0.004	<0.008	ND (0.003)	ND (0.003)	ND (0.003)
Silicon	7.00	MC	0.2	5.9	8	9.0	2.1	NR	11	NA	NA
Silver	ND	NR	0.005	.0005	NA	<0.001	<0.001	NR	ND (0.002)	0.003[c]	0.007[c]
Sodium	2.00	2	>1	140	NA	25.	1.6	NR	2.6	NA	NA
Strontium	3.00	6	0.06	NR	4	0.35	NR	NR	NR	NR	NR
Thallium	NR	NR	NR	NR	NR	NR	NR	NR	ND (0.002)	NA	NA
Titanium	0.100	0.1	<0.01	0.007	0.01	<0.005	0.018	NR	ND (0.005)	NA	NA
Vanadium	ND	0.007	0.003	0.045	0.07	<0.003	0.008	NR	ND (0.003)	NA	NA
Zinc	BC	0.1	4	0.003	0.05	0.018	0.050	0.15	0.48	NA	NA

Source: Refs. 1-8, and 16.

[a] BC = Less than or equal to the blank concentration.

[b] NR = Not reported.

[c] Result is less than 5 times the detection limit.

[d] NA = Not analyzed.

[e] ND = None detected.

[f] MC = Major component.

TABLE C-11. SUMMARY OF WATER QUALITY PARAMETERS IN RCRA EP EXTRACTS OF GASIFIER ASHES (mg/L)

Parameter	Wellman-Galusha (Fort Snelling)	Riley	Texaco (Ruhrchemie)	UGas IGT
pH (standard units)	4.13	9.5	5.18	4.8
Total Organic Carbon	NR[b]	474	NR	95
Chemical Oxygen Demand	1710	1240	NR	241
Chloride	NR	45	NR	0.8
Fluoride	NR	1.03	NR	<0.02
Total Dissolved Solids	2131	NR	280	185
Nitrate	<10	23	NR	0.37
Sulfate	NR	580	NR	2
Ammonia	<0.007	<2	NR	0.11
Cyanide	<0.02	<0.01	NR	<0.01
Phosphate	<0.01	1.3	NR	0.3
Phenol	0.002	<0.025	<0.018	0.016
Biological Oxygen Demand	2970	986	NR	NR

Source: Refs. 2, 4, 7, and 16.

[a] Values in mg/L except for pH.

[b] NR = Not reported.

TABLE C-12. ELEMENTAL CONCENTRATION IN ASTM EXTRACTS OF GASIFIER ASHES (mg/L)

Element	Chapman	Riley	Lurgi-Type (Kosovo)	Sasol I (Tristates)	IGT U-Gas Run A	IGT U-Gas Run B	KRW-WY Subbituminous	KRW-Pitts. #8	KRW-ND Lignite
Aluminum	<BC[a]	7.6	2	<0.050	NR[b]	NR	4.7	1.2	13
Antimony	ND[c]	<0.002	NA[d]	<0.005	0.0008	0.002	ND (0.03)	ND (0.03)	ND (0.03)
Arsenic	0.003	0.002	0.01	<0.002	0.030	0.009	ND (0.003)	ND (0.06)	ND (0.06)
Barium	<BC	<0.001/.120	0.05	0.066	<0.06	<0.02	0.28	0.38	2.0
Beryllium	ND	<0.002	NA	<0.0005	<0.002	<0.002	ND (0.0005)	ND (0.0005)	ND (0.0005)
Boron	NR	NR	NR	NR	NR	NR	ND (0.009)	0.14	1.3
Cadmium	ND	<0.0005	NA	<0.0005	<0.003	<0.003	ND (0.002)	ND (0.002)	0.004[e]
Calcium	>6.000	160	NA	330	NR	NR	28	92	84
Chromium	<BC	0.24/<.001	0.5	<0.002	<0.005	<0.005	ND (0.001)	ND (0.001)	0.071
Cobalt	<BC	.009	<0.007	<0.006	NR	NR	ND (0.006)	ND (0.006)	ND (0.006)
Copper	<BC	.012	0.03	<0.001	0.017	0.005	ND (0.001)	ND (0.001)	0.005[e]
Iron	ND	<0.008	0.1	<0.008	0.04	0.045	ND (0.008)	0.14	26
Lead	ND	<0.002	0.07	<0.002	<0.010	<0.010	0.003[e]	ND (0.084)	ND (0.084)
Lithium	ND	NR	0.07	1.1	NR	NR	ND (0.0005)	0.005	0.14
Magnesium	1.000	.47	NA	11	NR	NR	0.32	0.08	9.5
Manganese	0.001	.002	0.02	0.045	0.006	0.007	ND (0.001)	ND (0.03)	1.0
Mercury	NA	<0.0005	NA	<0.0002	<0.0002	<0.0008	ND (0.0002)	ND (0.03)	ND (0.03)
Molybdenum	<BC	0.069	0.05	0.096	NR	NR	ND (0.002)	0.01	0.01
Nickel	<BC	0.040	0.02	0.007	<0.010	<0.010	0.005[e]	ND (0.003)	ND (0.003)
Phosphorus	NR	NR	NR	NR	NR	NR	ND (0.2)	ND (0.2)	0.82[e]
Potassium	0.900	13	NA	83	NR	NR	ND (0.04)	0.47	3.4
Selenium	<BC	0.004	0.007	0.008	<0.002	<0.002	ND (0.03)	ND (0.084)	ND (0.084)
Silicon	0.100	.19	7	3.6	NR	NR	4.8	2.5	20
Silver	ND	<0.0005	NA	<0.001	<0.002	0.003	ND (0.002)	0.009[e]	ND (0.002)
Sodium	0.2	130	NA	85	NR	NR	1.6	1.5	31
Strontium	0.1	3	0.3	0.79	NR	NR	NR	NR	NR
Thallium	NR	NR	NR	NR	NR	NR	ND (0.002)	ND (0.091)	ND (0.091)
Titanium	<BC	.037	0.02	<0.005	NR	NR	ND (0.005)	ND (0.005)	0.60
Vanadium	ND	.045	0.004	0.020	NR	NR	ND (0.003)	ND (0.003)	ND (0.049)
Zinc	1	.003	0.08	<0.003	0.05	0.15	ND (0.003)	ND (0.003)	0.011[e]

Source: Refs. 1, 4, 6, 8, 15, and 16.

[a] <BC = Below blank concentration.

[b] NR = Not reported.

[c] ND = Not detected (detection limit).

[d] NA = Not analyzed.

[e] Result is less than 5 times the detection limit.

TABLE C-13. SUMMARY OF WATER QUALITY PARAMETERS IN ASTM[a] EXTRACTS OF GASIFIER ASHES

Parameter	Riley	Sasol I (Tristates)	Texaco (Ruhrchemie)	IGT U-Gas Run A	IGT U-Gas Run B	KRW-WY Subbituminous
Initial pH	10.7	5	6.35	7	8	NA
Final pH	NA[b]	8.4	NA	10.6	10.6	10.3
Final Alkalinity as $CaCO_3$	NA	14	NA	94	97	NA
Bicarbonate	NA	14	NA	NA	NA	24
Carbonate	NA	<1	NA	NA	NA	75
Total Organic Carbon	2.7	<1	NA	7.2	1.0	<1.0
Chemical Oxygen Demand	23	44	NA	24	5	NA
Chloride	19	16	NA	1.9	5.5	1.4
Total Inorganic Carbon	NA	NA	NA	NA	NA	3
Fluoride	0.26	0.2	NA	<0.02	<0.02	0.57
Total Dissolved Solids	NA	1820	150	150	115	NA
Conductivity	NA	1530	220	NA	NA	237
Nitrate -N	23	0.3	NA	0.31	0.34	NA
Nitrate/Nitrite	NA	NA	NA	NA	NA	ND (0.02)[c]
Sulfate	500	1030	NA	NA	9	NA
Sulfite	NA	8	NA	NA	NA	NA
Sulfide	NA	<1	NA	NA	NA	NA
Odor (Threshold number)	NA	NA	NA	1	1	NA
Ammonia	<2	NA	NA	NA	NA	NA
Oil and Grease	NA	NA	NA	1	<1	NA
Cyanide	NA	NA	NA	<0.01	<0.01	<0.01
Thiocyanate	<0.01	NA	NA	NA	NA	NA
Fluoride	<4	NA	NA	NA	NA	NA
Total Phosphate as P	0.92	NA	NA	0.21	0.03	NA
Phenol	<0.025	NA	NA	<0.01	<0.01	<0.005
BOD	<1	NA	NA	NA	NA	NA
Total Hardness	NA	NA	NA	65	90	NA
Calcium	NA	NA	NA	60	65	NA
Magnesium	NA	NA	NA	0.4	0.37	NA
Sodium	NA	NA	NA	1.4	6.3	NA
Potassium	NA	NA	NA	2.5	4.1	NA

Source: Refs. 4, 15, 7, 16, and 8.

[a] Values in mg/L except for pH and color.

[b] NA = Not analyzed.

[c] ND ( ) = Not detected (detection limit).

TABLE C-14. PERCENT SOLUBLE ELEMENTS IN RCRA AND ASTM EXTRACTS OF GASIFIER ASH FROM CHAPMAN

Element	Solids Concentration (mg/Kg)	Acidic Leaching: EP Extract Concentration (mg/L)	Acidic Leaching: Percent Soluble (%)	Neutral Leaching: ASTM Extract Concentration (mg/L)	Neutral Leaching: Percent Soluble (%)
Aluminum	3,020	<BC[a]	-	<BC	-
Antimony	200	ND[b]	-	ND	-
Arsenic	<0.4	0.010	25	0.003	≥3
Barium	2,000	2.00	2	<BC	-
Beryllium	10	ND	-	ND	-
Cadmium	<9	ND	-	ND	-
Calcium	50,000	>6	≥0.2	>6	0.05
Chromium	30	<0.003	0.2	<BC	-
Cobalt	50	<BC	-	<BC	-
Copper	1,000	0.030	0.6	<BC	-
Iron	1,000	5.00	10	ND	-
Lead	20	0.010	1	ND	-
Lithium	70	ND	-	ND	-
Magnesium	6,000	>9.96	≥3	1.	0.07
Manganese	NR[c]	0.100	-	0.001	-
Mercury	NR	NA[d]	-	NA	-
Molybdenum	NR	<BC	-	<BC	-
Nickel	NR	<BC	-	<BC	-
Potassium	10,000	5,000	1,000	0.900	0.01
Selenium	30	0.002	0.1	<BC	-
Silicon	7,000	7.00	2	0.100	<1
Silver	NR	ND	-	ND	-
Sodium	NR	2.00	-	0.2	-
Strontium	2,000	3.00	3	0.1	0.02
Titanium	3,000	0.100	0.07	<BC	-
Vanadium	30	ND	-	ND	-
Zinc	NR	<BC	-	1	-

Source: Ref. 1.

[a] <BC = Below blank concentration.

[b] ND = Not detected.

[c] NR = Not reported.

[d] NA = Not analyzed.

TABLE C-15. PERCENT SOLUBLE ELEMENTS IN RCRA EXTRACTS OF GASIFIER ASH FROM WELLMAN-GALUSHA (GLEN-GERY)[a]

Element	Solids Concentration (mg/Kg)	Acidic Leaching EP Extract Concentration (mg/L)	Acidic Leaching Percent Soluble (%)
Aluminum	>1,000	0.006	0.01
Antimony	0.5[b]	NR[c]	-[d]
Arsenic	3[b]	0.004	2
Barium	>1,000	0.1	≤2
Beryllium	1	NR	-
Cadmium	0.4	0.001	5
Calcium	>1,000	0.099	0.2
Chromium	190	0.002	0.02
Cobalt	23	0.001	0.09
Copper	200	0.008	0.08
Iron	>1,000	0.01	0.02
Lead	12	0.008	1
Lithium	>240	0.03	≤3
Magnesium	>1,000	0.036	0.07
Manganese	69	0.005	0.1
Mercury	0.28	ND[e]	-
Molybdenum	0.28	0.02	143
Nickel	34	NR	-
Potassium	>1,000	>6	12
Selenium	2	<0.001	1
Silicon	>1,000	0.2	4
Silver	1	0.005	0.01
Sodium	>1,000	>1	2
Strontium	490	0.06	0.2
Titanium	>1,000	<0.01	≤0.02
Vanadium	200	0.003	0.03
Zinc	18	4	444

Source: Ref. 3.

[a] Analyses by ICPES except as noted.

[b] Analysis by AAS.

[c] NR = not reported.

[d] Dashes mean cannot be determined from available data.

[e] ND = not detected.

TABLE C-16. PERCENT SOLUBLE ELEMENTS IN RCRA EXTRACTS OF GASIFIER ASH FROM WELLMAN-GALUSHA (FORT SNELLING)[a]

		Acidic Leaching	
Element	Solids Concentration (mg/Kg)	EP Extract Concentration (mg/L)	Percent Soluble (%)
Aluminum	19,100	0.1	0.01
Antimony	<0.4[b]	NR[c]	NR
Arsenic	30	0.005	0.3
Barium	1,900	1	1
Beryllium	NR	NR	NR
Cadmium	<6.2	<0.007	2
Calcium	48,800	MC	-
Chromium	22	0.001	0.1
Cobalt	<190	0.007	≥74
Copper	33	0.1	6
Iron	30,400	2	0.1
Lead	>87	0.007	0.2
Lithium	NR	0.006	NR
Magnesium	12,300	MC	-
Manganese	64	0.5	15.6
Mercury	1.7	NR	-
Molybdenum	<50	0.01	0.4
Nickel	71	0.04	1
Potassium	NR	MC	-
Selenium	15	0.005	0.6
Silicon	NR	MC	-
Silver	<6.21	NR	-
Sodium		2	105
Strontium		6	48
Titanium	1,200	0.1	0.2
Vanadium	38	0.007	0.4
Zinc	25	0.1	8

Source: Ref. 2.

[a] Analyses by ICPES except as noted.

[b] Analysis by AAS.

[c] NR=Not reported.

[d] MC= Major component.

TABLE C-17. PERCENT SOLUBLE ELEMENTS IN RCRA AND ASTM EXTRACTS OF GASIFIER ASH FROM RILEY[a]

		Acidic Leaching		Neutral Leaching	
Element	Solids Concentration (mg/Kg)	EP Extract Concentration (mg/L)	Percent Soluble (%)	ASTM Extract Concentration (mg/L)	Percent Soluble (%)
Aluminum	45,000	<0.050	<<1[b]	7.6	0.06
Antimony	0.57[c]	0.002	7.	<0.002	1.4
Arsenic	56[c]	680	>100%[d]	0.002	0.01
Barium	3,400	0.003	0.02	0.120[c]	0.01
Beryllium	0.3	<0.002	≤100	<0.002	2.7
Cadmium	NR[e]	<0.0005	-	<0.0005	-
Calcium	96,000	1,400	30	160	0.7
Chromium	<0.2	<0.001	10	<0.001	2
Cobalt	17	<0.006	0.7	0.009	0.2
Copper	44	<0.001	0.04	0.012	0.1
Iron	56,000	<0.008	<<1	<0.008	<<1
Lead	8[b]	<0.002	0.5	<0.002	0.1
Lithium	6[b]	0.002	0.7	NR	NR
Magnesium	22,000	24	2	0.47	0.01
Manganese	250	0.003	<<1	0.002	0.003
Mercury	NR	<0.0005	-[g]	<0.005	-
Molybdenum	23	0.058	5	0.069	1.2
Nickel	26	0.02	1	0.040	0.6
Potassium	7,000	15	4	13	0.7
Selenium	<1	0.006	12	0.004	-
Silicon	MC[f]	5.9	-[g]	0.19	-
Silver	3[b]	0.0005	0.3	<0.0005	0.07
Sodium	24,000	140	10	130	2
Strontium	MC	NR	-[g]	3	-
Titanium	2,200	0.007	<4	0.037	0.007
Vanadium	90	0.045	1	0.045	0.2
Zinc	38	0.003	2	0.003	0.03

Source: Ref. 4.

[a] Analyses by ICPES except as noted.

[b] <<1 represents $\leq 10^{-4}$.

[c] Analyses by AAS.

[d] Analytical error suspect.

[e] NR = not reported.

[f] MC = major component.

[g] Dashes mean cannot be determined from available data.

TABLE C-18. PERCENT SOLUBLE ELEMENTS IN RCRA AND ASTM EXTRACTS OF GASIFIER ASH FROM LURGI-TYPE GASIFIER[a]

		Acidic Leaching		Neutral Leaching	
Element	Solids Concentration (mg/Kg)	EP Extract Concentration (mg/L)	Percent Soluble (%)	ASTM Extract Concentration (mg/L)	Percent Soluble (%)
Aluminum	2	0.01	0.01	2	>100
Antimony	<0.2[b]	<0.002	<<1[c]	NA[d]	–[e]
Arsenic	75[b]	<0.004	<<1	0.01	<<1
Barium	0.05	3	>100%	0.05	>100
Beryllium	2.5[b]	NA	–	NA	–
Cadmium	69[b]	NA	–	NA	–
Calcium	NA	NA	–	NA	–
Chromium	180[b]	0.3	3.3	0.5	1.1
Cobalt	17[b]	<0.001	0.3	<0.007	0.2
Copper	40[b]	0.01	0.5	0.03	0.3
Iron	0.1	10	>100%[f]	0.1	>100
Lead	52[b]	0.008	0.3	0.07	0.5
Lithium	0.07	0.03	>100	0.07	>100
Magnesium	NA	2	–	NA	–
Manganese	0.02	0.001	100	0.02	>100
Mercury	0.3[b]	NA	–	NA	–
Molybdenum	8.9[b]	0.1	22	0.05	2.2
Nickel	320[b]	0.04	0.25	0.02	0.03
Potassium	NA	NA	–	NA	–
Selenium	24[b]	0.01	0.8	0.007	0.1
Silicon	7	8	>100	7	>100
Silver	NA	NA	–	NA	–
Sodium	NA	NA	–	NA	–
Strontium	370[b]	4	22	0.3	0.3
Titanium	0.02	0.01	>100	0.02	>100
Vanadium	100[b]	0.07	1.4	0.004	0.02
Zinc	21[b]	0.05	4.8	0.08	1.5

Source: Ref. 6.

[a] Analysis by ICPES except as noted.

[b] Analysis by AAS.

[c] <<1 represents $\leq 10^{-4}$.

[d] NA = not analyzed.

[e] Dash means cannot be determined from available data.

[f] Analytical data suspect.

TABLE C-19. PERCENT SOLUBLE ELEMENTS IN RCRA EXTRACTS OF GASIFIER ASH FROM TEXACO (RUHRCHEMIE)[a]

Element	Solids Concentration (mg/Kg)	Acidic Leaching EP Extract Concentration (mg/L)	Acidic Leaching Percent Soluble (%)
Aluminum	73,000	0.15	0.004
Antimony	<1.2	<0.005	8.3
Arsenic	43	<0.003	0.1
Barium	420	0.019	0.09
Beryllium	0.7	<0.0005	1.4
Cadmium	0.65	<0.0005	1.5
Calcium	32,000	9.3	0.6
Chromium	160	0.009	0.1
Cobalt	34	3.3	>100
Copper	55	0.079	2.8
Iron	81,000	0.018	<<1[b]
Lead	32	<0.002	0.1
Lithium	25	NA[c]	-[d]
Magnesium	5,300	0.73	<<1
Manganese	380	0.061	0.06
Mercury	NA	<0.0005	-
Molybdenum	45	0.008	0.4
Nickel	130	NA	-
Potassium	12,000	1.4	0.23
Selenium	14	<0.004	0.6
Silicon	MC[e]	2.1	-
Silver	0.72	<0.001	≤2.8
Sodium	5,700	1.6	0.6
Strontium	NR[f]	NR	NR
Titanium	5,200	0.018	<<1
Vanadium	180	0.008	0.09
Zinc	280	0.050	0.4

Source: Ref. 7.

[a] Analyses by ICPES.

[b] <<1 represents $<10^{-4}$.

[c] NA = Not analyzed.

[d] Dash means cannot be determined from available data.

[e] MC = Major component.

[f] NR = Not reported.

TABLE C-20. ASTM LEACHABLE ORGANICS FROM KRW ASH

	MW[a]	LOC[b]	Pittsburgh #8 Composite	ND Lignite Composite
Naphthalene	128	1	ND[c]	ND
Methylnaphthalene	142		ND	ND
Acenaphthylene	152		ND	ND
Biphenyl	154		ND	ND
Acenaphthene	154		ND	ND
Fluorene	166		ND	ND
Anthracene	178		ND	ND
Phenanthrene	178		ND	ND
Fluoranthene	202		ND	ND
Pyrene	202		ND	ND
Benzo(a)anthracene	228		ND	ND
Chrysene	228		ND	ND
Benzo(b)fluoranthene	252		ND	ND
Benzo(k)fluoranthene	252		ND	ND
Benzo(a)pyrene	252		ND	ND
Indeno(1,2,3-c,d)pyrene	276		ND	ND
Benzo(g,h,i)perylene	276		ND	ND
Dibenzo(a,h)anthracene	278		ND	ND
S Compounds				
Benzothiophene	134		ND	ND
N Compounds				
Aniline	93		4	ND
Carbazole	167		ND	ND
O Compounds				
Phenol	94		ND	ND
Cresol	108		ND	ND
Dimethylphenol	122		ND	ND
Dibenzofuran	168		ND	ND

Source: Ref. 8.

[a] MW = Molecular weight.

[b] LOC = Level of confidence in identification (1-High, sample matched standards in retention time and mass spectra; 2-Good, sample spectra matched library spectra very well; 3-Moderate, identified compound is best match available against library spectra).

[c] ND = Not detected at 1 mg/L (ppm). Results of CC-MS analysis of ASTM leachate reported in concentration units of ug/L (ppb).

APPENDIX D

DATA COMPILATION FOR CYCLONE DUSTS

TABLE D-1. SUMMARY OF SPARK SOURCE MASS SPECTROGRAPHIC ANALYSIS OF CYCLONE DUSTS (mg/Kg dust)

Element	Wellman-Galusha (Fort Snelling)	Wellman-Galusha (Glen-Gery)	Riley	Foster-Wheeler/ STOIC	Lurgi-type (Kosovo)	Texaco (Ruhrchemie)
Aluminum	100	NR[a]	>1000	>1000	>1000	MC[b]
Antimony	100	NR	53	2	4	9
Arsenic	<0.04	NR	83	19	40	49
Barium	500	NR	>1000	>1000	>1000	MC
Beryllium	NR	0.4	3	0.7	0.8	2
Bismuth	NR	0.3	5	0.2	4	0.5
Boron	7	NR	11	190	400	370
Bromine	NR	9	2	3	7	5
Cadmium	NR	2	2	<0.1	3	1
Calcium	2000	NR	>1000	>1000	>1000	MC
Cerium	20	15	99	24	28	86
Cesium	NR	0.7	15	3	0.7	19
Chlorine	NR	NR	100	51	86	26
Chromium	30	11	58	26	220	450
Cobalt	3	5	10	2	1	20
Copper	900	30	68	12	64	79
Dysprosium	NR	0.6	2	4	4	3
Erbium	NR	0.3	0.9	0.8	0.8	4
Europium	NR	0.4	1	1	1	2
Fluorine	100	280	240	140	>1000	MC
Gadolinium	NR	0.4	1	2	2	3
Gallium	<10	33	220	12	280	86
Germanium	NR	6	11	2	19	26
Gold	NR	<0.1	<0.1	<0.1	<0.2	ND[c]
Hafnium	NR	<0.1	3	0.5	<2	1
Holmium	NR	0.4	1	1	1	2
Iodine	NR	0.4	24	0.9	4	2
Iridium	NR	<0.1	<0.1	<0.1	ND	ND

(Continued)

TABLE D-1. (Continued)

Element	Wellman-Galusha (Fort Snelling)	Wellman-Galusha (Glen-Gery)	Riley	Foster-Wheeler/ STOIC	Lurgi-type (Kosovo)	Texaco (Ruhrchemie)
Iron	2000	NR	>1000	>1000	>1000	MC
Lanthanum	20	8	130	24	20	61
Lead	60	8	230	37	870	86
Lithium	2	6	160	10	27	41
Lutetium	NR	<0.1	0.3	0.1	ND	0.3
Magnesium	500	NR	>1000	>1000	>1000	MC
Manganese	200	NR	570	310	97	600
Molybdenum	NR	NR	57	4	9	66
Neodymium	NR	2	110	10	2	12
Nickel	100	3	47	4	3	190
Niobium	NR	4	52	12	10	24
Osmium	NR	5	<0.1	<0.1	ND	ND
Palladium	NR	<0.1	<0.1	<0.1	ND	ND
Phosphorous	8000	NR	>1000	>1000	>1000	<C
Platinum	NR	<0.1	<0.1	<0.1	ND	ND
Potassium	4000	NR	>1000	>1000	>1000	MC
Praseodymium	NR	2	35	5	5	12
Rhenium	NR	<0.1	<0.1	<0.1	ND	ND
Rhodium	NR	NR	<0.1	<0.1	ND	ND
Rubidium	3	3	15	31	9	150
Ruthenium	NR	<0.1	<0.1	<0.1	ND	ND
Samarium	NR	2	11	4	4	12
Scandium	2	5	7	2	1	34
Selenium	NR	NR	16	3	10	16
Silicon	2000	NR	>1000	>1000	>1000	MC
Silver	NR	2	5	<0.1	<2	1
Sodium	NR	NR	>1000	>1000	>480	MC
Strontium	50	NR	270	>1000	760	310
Sulfur	300	NR	>1000	NR	>1000	MC
Tantalum	NR	<0.1	<0.1	<0.1	ND	1
Tellurium	NR	0.2	0.9	0.2	1	0.3
Terbium	NR	0.1	0.6	2	0.8	0.6
Thallium	NR	0.9	22	1	12	13
Thorium	NR	2	97	4	8	25
Thulium	NR	<0.2	0.2	0.1	ND	0.4
Tin	NR	2	39	0.8	77	11

(Continued)

TABLE D-1. (Continued)

Element	Wellman-Galusha (Fort Snelling)	Wellman-Galusha (Glen-Gery)	Riley	Foster-Wheeler/ STOIC	Lurgi-type (Kosovo)	Texaco (Ruhrchemie)
Titanium	200	NR	>1000	>1000	>1000	MC
Tungsten	NR	<0.7	5	2	4	1
Uranium	NR	0.9	45	3	7	46
Vanadium	20	19	150	30	30	150
Ytterbium	NR	0.6	2	0.9	ND	3
Yttrium	10	13	42	7	16	77
Zinc	NR	160	>1000	60	560	970
Zirconium	30	29	110	59	55	95

Sources: Refs. 2-7
[a]NR = Not reported.
[b]MC = Major component.
[c]ND = None detected.

TABLE D-2. SUMMARY OF INDUCTIVELY COUPLED ARGON PLASMA EMISSION SPECTROGRAPHIC ANALYSIS OF GASIFIER CYCLONE DUSTS (mg/Kg dust)

Element	Wellman-Galusha (Fort Snelling)	Foster-Wheeler/ STOIC	Texaco (Ruhrchemie)
Aluminum	7200	26000	83000
Antimony	NR[a]	NR	8.2
Arsenic	<100	NR	60
Barium	2300	320	455
Beryllium	NR	NR	19
Boron	118	98	1040
Cadmium	<6.2	NR	13.2
Calcium	11300	1200	29000
Chromium	<6.2	20	200
Cobalt	<190	4.3	38
Copper	<6.2	22	71
Iron	7900	1200	7.7
Lead	<86	NR	220
Magnesium	12300	2400	6100
Manganese	23	48	380
Molybdenum	<49	7.6	130
Nickel	<25	16	130
Phosphorous	NR	NR	2900
Potassium	NA[b]	2700	16000
Selenium	NR	NR	29
Silicon	NA	NA	150000
Silver	<6.2	690	0.61
Sodium	6200	NR	7300
Strontium	1180	NR	NR
Titanium	317	780	5600
Vanadium	<12	24	140
Zinc	15	620	1750

Sources: Refs. 2, 5, and 7.

[a] NR = Not reported.

[b] NA = Not analyzed.

TABLE D-3. SUMMARY OF ATOMIC ABSORPTION SPECTROPHOTOMETRIC ANALYSIS OF GASIFIER CYCLONE DUSTS (mg/Kg dust)

Element	Chapman	Wellman-Galusha (Fort Snelling)	Wellman-Galusha (Glen-Gery)	Riley	Foster Wheeler/ STOIC	Texaco (Ruhrchemie)
Arsenic	<0.4	66	85	1.700	31	43
Antimony	100	<0.4	53	0.6	19	<1.2
Cadmium	NA[a]	NA	NA	NA	NA	0.65
Lead	NA	NA	NA	NA	NA	32
Mercury	NA	2.1	280	0.02	0.75	0.55
Nickel	NA	NA	NA	NA	NA	130
Selenium	NA	13	NA	1.2	2.6	4.7
Silver	NA	NA	NA	NA	NA	0.72

Sources: Refs. 1-5 and 7.
[a]NA = Not analyzed by AAS.

TABLE D-4. SUMMARY OF ASH MINERAL ANALYSIS OF GASIFIER CYCLONE DUSTS[a]

Components	Wellman-Galusha (Fort Snelling)	Texaco (Ruhrchemie)
SiO_2	20.71	51.61
Al_2O_3	12.21	20.65
TiO_2	0.35	1.02
Fe_2O_3	6.95	14.66
CaO	21.55	4.56
MgO	6.82	1.43
K_2O	0.81	2.42
Na_2O	7.83	1.41
SO_3	17.02	1.84
P_2O_5	0.70	0.23
SrO	0.85	0.04
BaO	2.01	0.06
Mn_3O_4	0.01	0.07
Undetermined	2.18	0.00
	100.0	100.0

Sources: Refs. 2 and 7.

[a] Values listed as % of ashed cyclone dust.

TABLE D-5. SUMMARY OF PROXIMATE/ULTIMATE ANALYSIS OF GASIFIER CYCLONE DUSTS

Analysis	Chapman	Wellman-Galusha (Fort Snelling)	Wellman-Galusha (Glen-Gery)	Riley	Foster Wheeler/ STOIC	Lurgi-type (Kosovo)	Texaco (Ruhrchemie)
PROXIMATE							
Moisture (%)	ND[b]	0.44	0.71	0.59	1.25	24	-
Ash (%)		18.89	24.70	38.21	28.48	15	75.48
Volatile (%)	ND	24.30	2.88	14.84	2.03	35	3.75
Fixed Carbon (%)	NR[c]	56.37	71.71	46.36	68.24	27	20.77
BTU/lb (Kcal/Kg)	N	10670(5928)	10935(6075)	8607(4782)	9922(5512)	6768(3760)	3472(1929)
Sulfur (%)	-	1.50	-	1.59	0.87	2.9	-
ULTIMATE							
Moisture (%)	-	0.44	0.71	0.59	1.25	24	-
Carbon (%)	92.42	66.88	70.14	54.48	69.51	35	18.72
Hydrogen (%)	0.93	2.31	1.36	1.48	0.55	4	0.21
Nitrogen (%)	1.69	0.93	0.62	0.83	0.66	21	0.70
Chlorine (%)	NR	0.03	0.01	0.00	0.01	-	0.05
Sulfur (%)	0.70	1.50	1.51	1.59	0.87	1.1	1.73
Ash (%)	-	18.89	24.70	38.21	28.48	19	79.56
Oxygen (% dif)	4.26	9.02	0.95	2.82	-1.33	-	-
	100.00	100.0	100.01	100.0	100.00	108.1	100.97

(Continued)

TABLE D-5. (Con't)

KRW-WY SUBBITUMINOUS TEST						
	Primary Cyclone		Secondary Solids		Composite[a] (95% x 1°)+(5% x 2°)	
Analysis	as rec'd	dry	as rec'd	dry	as rec'd	dry
PROXIMATE						
Moisture (%)	2.91	--	0.90	--	2.81	--
Ash (%)	40.20	41.40	44.54	44.95	40.42	41.58
Volatile (%)	7.26	7.43	3.90	3.94	7.09	7.26
Fixed Carbon (%)	49.64	51.17	50.65	51.12	49.69	51.17
ULTIMATE						
Moisture (%)	2.91	--	0.90	--	2.81	--
Carbon (%)	55.08	56.72	52.90	53.38	54.97	56.55
Hydrogen (%)	0.60	0.61	0.46	0.46	0.59	0.60
Nitrogen (%)	0.46	0.48	0.27	0.27	0.45	0.47
Chlorine (%)	0.02	0.02	0.03	0.03	0.02	0.02
Sulfur (%)	0.50	0.51	0.48	0.48	0.50	0.48
Ash (%)	40.20	41.40	44.54	44.95	40.42	41.58
Oxygen (%)	0.25	0.26	0.40	0.42	0.26	0.27
Btu/lb (Kcal/Kg)	8079 (4488)	8320 (4622)	7960 (4422)	8032 (4462)	8073 (4485)	8306 (4614)

(Continued)

TABLE D-5. (Con't)

	KRW-PITTSBURGH #8					
	Primary Cyclone		Secondary Solids		Composite (95% x 1°)+(5% x 2°)	
	as rec'd	dry	as rec'd	dry	as rec'd	dry
PROXIMATE						
Moisture (%)	2.29	--	3.90	--	2.37	--
Ash (%)	20.26	20.74	20.89	21.76	20.29	20.79
Volatile (%)	1.64	1.68	0.91	0.95	1.60	1.64
Fixed Carbon (%)	75.81	77.58	74.31	77.66	75.74	77.58
ULTIMATE						
Moisture (%)	2.29	--	3.90	--	2.37	--
Carbon (%)	74.52	76.27	72.46	75.33	74.42	76.22
Hydrogen (%)	0.29	0.30	0.13	0.13	0.28	0.29
Nitrogen (%)	0.53	0.54	0.44	0.46	0.53	0.54
Chlorine (%)	0.00	0.00	0.01	0.01	0.00	0.00
Sulfur (%)	2.37	2.43	1.66	1.73	2.33	2.40
Ash (%)	20.76	20.74	20.89	21.76	20.29	20.79
Oxygen (%)	-0.26	-0.27	0.56	0.57	-0.22	-0.22
Btu/lb (Kcal/Kg)	10,977 (6098)	11,234 (6241)	10,686 (5937)	11,115 (6175)	10,962 (6090)	11,228 (6238)

(Continued)

TABLE D-5. (Con't)

KRW-ND LIGNITE TEST

Analysis	Primary Cyclone		Secondary Solids		Composite (95% x 1°)+(5% x 2°)	
	as rec'd	dry	as rec'd	dry	as rec'd	dry
PROXIMATE						
Moisture (%)	1.06	--	1.31	--	1.07	--
Ash (%)	38.47	38.87	36.12	36.61	38.35	38.76
Volatile (%)	7.49	7.58	7.91	8.01	7.51	7.60
Fixed Carbon (%)	52.98	53.56	54.66	55.38	53.06	53.65
ULTIMATE						
Moisture (%)	1.06	--	1.31	--	1.07	--
Carbon (%)	57.33	57.94	56.39	57.14	57.28	57.90
Hydrogen (%)	0.52	0.52	0.49	0.50	0.52	0.52
Nitrogen (%)	0.49	0.49	0.45	0.46	0.49	0.49
Chlorine (%)	0.02	0.02	0.01	0.01	0.02	0.02
Sulfur (%)	2.00	2.02	2.08	2.11	2.00	2.02
Ash (%)	38.47	38.87	36.12	36.61	38.35	38.76
Oxygen (%)	0.12	0.14	3.14	3.18	0.271	0.292
Btu/lb (Kcal/Kg)	8483 (4713)	8573 (4763)	8287 (4604)	8397 (4665)	8473 (4707)	8564 (4758)

[a] Values are the result of combining 95% x primary cyclone solids values and 5% x secondary cyclone solids values. The 95/5 ratio was obtained by comparing catch flow rates of the first and second cyclones.

[b] ND = Not determined.

[c] NR = Not reported.

Sources: Refs. 1-8.

TABLE D-6. SUMMARY OF RADIOACTIVE SPECIES ANALYSIS OF GASIFIER CYCLONE DUSTS (pCi/g)

Species	Wellman-Galusha (Fort Snelling)	Wellman-Galusha (Glen-Gery)	Riley	Texaco (Ruhrchemie)	KRW		
					WY Subbi-tuminous	Pitts-burgh #8	ND Lignite
Po-210	2.500	NR[a]	1.0180	NR	NA[b]	1.2 ± 0.1	1.8 ± 0.1
Ra-226	2.000	NR	3.700	2.7			
Ra-228	NR	NR	NR	NR	NR	1.3 ± 0.3	0.83 ± 0.25
U-234	0.675	NR	0.8399	NR			
U-235	0.388	NR	0.09286	ND[c]			
U-238	0.731	NR	0.8631	NR			
K-40	NR	NR	6.8000	NR			
P6-214	NR	NR	1.5000	23			
Bi-214	NR	NR	1.3000	23			
Th-233	NR	NR	0.8000	NR			
Th-227	ND	NR	0.1146	NR			
Th-228	0.528	NR	0.6016	NR			
Th-230	0.639	NR	0.8474	NR			
Th-232	0.417	NR	0.5685	12			
Pb-210	1.392	NR	0.9660	28			
Pb-212	NR	NR	NR	2			
Gross Alpha	11.1 ± 6.1	8.4 ± 2.4	17 ± 7	81 ± 15	16 ± 4[d] 23 ± 7/ 27 ± 7[d]	21 ± 7	<9.5
Gross Beta	0 ± 15	6.0 ± 9.0	0 ± 15	67 ± 8	35 ± 8/	19 ± 10	<20

Sources: Refs. 2, 3, 4, 7 and 8.

[a] NR = Not reported.

[b] NA = Not analyzed.

[c] ND = Not detected.

[d] Duplicate values; quality control sample.

TABLE D-7. SUMMARY OF RESULTS OF GC-MS ORGANIC ANALYSIS OF CYCLONE DUSTS[a]

Compound	Wellman-Galusha (Glen-Gery)	Riley	Foster Wheeler/ STOIC	Texaco (Ruhrchemie) Run A	Texaco (Ruhrchemie) Run B
Appendix A Base/Neutral Extractable Compounds					
Acenaphthene	NR[b]			ND(4)[c]	ND(4)
Acenaphthalene	NR	0.8		ND(4)	ND(4)
Anthracene	0.1		ND	ND(4)	ND(4)
Benzidine	0.1		ND	ND(4)	ND(4)
Benzo(a)pyrene	0.1	1.5	ND	ND(4)	ND(4)
3,4-Benzofluoranthene	0.1	NR	NR	ND(4)	ND(4)
Benzo(g,h,i)perylene	0.1	NR	NR	ND(10)	ND(10)
Benzo(k)fluoranthene	0.1	NR	NR	ND(4)	ND(4)
Bis(2-chloroethoxy)methane	0.1	NR	NR	ND(4)	ND(4)
Bis(2-chloroethyl)ether	0.1	NR	NR	ND(4)	ND(4)
Bis(2-chloroisopropyl)ether	0.1	NR	NR	ND(4)	ND(4)
Bis(2-ethylhexyl)phthalate	2	NR	ND	29[d]	37[d]
4-Bromophenyl phenyl ether	NR	NR		ND(4)	ND(4)
Butyl benzyl phthalate	NR	NR		ND(4)	ND(4)
2-Chloronaphthalene	NR	NR		ND(4)	ND(4)
4-Chlorophenyl phenyl ether	NR	NR		ND(4)	ND(4)
Chrysene	NR	2.2	NR	ND(4)	ND(4)
Dibenzo(a,h)anthracene	NR	NR	NR	ND(10)	ND(10)
1,2-Dichlorobenzene	NR	NR	NR	ND(4)	ND(4)
1,3-Dichlorobenzene	NR	NR	NR	ND(4)	ND(4)
1,4-Dichlorobenzene	NR	NR	NR	ND(4)	ND(4)
3,3-Dichlorobenzidine	NR	NR	NR	ND(4)	ND(4)
Diethyl phthalate	0.2	0.7	NR	ND(4)	ND(4)
Dimethyl phthalate	0.2	NR	NR	ND(4)	ND(4)
Di-n-butyl phthalate	0.2	NR	NR	ND(4)	ND(4)
2,4-Dinitrotoluene	NR	NR	NR	ND(4)	ND(4)
2,6-Dinitrotoluene	NR	NR	NR	ND(4)	ND(4)
Di-n-octyl phthalate	NR	NR	NR	ND(4)	ND(4)
1,2-Diphenyl hydrazine (as azobenzene)	NR	NR	NR	ND(4)	ND(4)
Fluoranthene	NR	0.8	NR	ND(4)	ND(4)
Fluorene	0.1	NR	NR	ND(4)	ND(4)
Hexachlorobenzene	NR	NR	NR	ND(4)	ND(4)
Hexachlorobutadiene	NR	NR	NR	ND(4)	ND(4)
Hexachlorocyclopentadiene	NR	NR	NR	ND(4)	ND(4)
Hexachloroethane	NR	NR	NR	ND(4)	ND(4)
Indeno(1,2:c,d)pyrene	NR	NR	NR	ND(10)	ND(10)
Isophorone	NR	NR	NR	ND(4)	ND(4)
Naphthalene	0.4	1.5	0.15	ND(4)	ND(4)
1-Methylnaphthalene	NR	NR	0.01	NR	NR
2-Methylnaphthalene	NR	NR	0.01	NR	NR
Dimethylnaphthalene	NR	NR	0.05	NR	NR
Nitrobenzene	NR	NR	NR	ND(4)	ND(4)
N-Nitrosodimethylamine	NR	NR	NR	ND(20)	ND(20)
N-Nitrosodi-N-propylamine	NR	NR	NR	ND(4)	ND(4)
N-Nitrosodiphenylamine (detected as diphenylamine)	NR	NR	NR	ND(4)	ND(4)
Phenanthrene	NR	0.9	NR	ND(4)	ND(4)
Pyrene	NR	0.7	0.04	ND(4)	ND(4)
1,2,4-Trichlorobenzene	NR	NR	NR	ND(4)	ND(4)

Sources: Refs. 3, 4, 5 and 7.

TABLE D-8. SUMMARY OF PHYSICAL CHARACTERISTICS OF GASIFIER CYCLONE DUSTS[a]

Parameter	Wellman-Galusha (Glen-Gery)	Riley	Texaco (Ruhrchemie) Run A	Texaco (Ruhrchemie) Run B
Bulk Density, lb/ft^3(g/m^3)				
Compacted			24.3 (0.18)	30.7 (0.22)
Uncompacted			18.0 (0.13)	22.0 (0.16)
Specific Gravity			2.118	2.235
Ash Fusion Temperature (°F)[b]				
Initial Deformation			2040(2300)	2090(2280)
Softening (H = W)			2060(2310)	2100(2300)
Softening (H - 1/2W)			2140(2350)	2120(2340)
Fluid			2200(2400)	2280(2410)
Particle Size Determination[c]				
Particle Diameter	% Mass Retained		A	B
2 mm			0	0.1
1 mm	1.00	0.758		
710 um	0.25	3.24	1.1	1.9
425	0.32		2.2	3.8
250		37.4	11.4	11.9
150	5.65		40.7	28.1
125	8.65	65.7		
75	26.84		19.9	28.1
<75	57.29	0	24.7	34.9

Source: Refs. 3, 4 and 7.

[a] All values determined for moisture-free solids.

[b] Values are for reducing atmosphere (oxidizing atmosphere).

[c] Particle size determination as percent mass retained on sieve.

TABLE D-9. SUMMARY OF CYCLONE DUST LEACHATE COMPOSITIONS FOR RCRA EXTRACTS[a]

	Elements							
Processes	Arsenic	Barium	Cadmium	Chromium	Lead	Selenium	Mercury	Silver
Chapman	0.02	<0.3	<0.002	<0.008	<BC[b]	<0.002	NR[c]	0.002
Wellman-Galusha (Fort Snelling)	0.02	1	NR	0.001	0.008	0.006	NR	NR
Wellman-Galusha (Glen-Gery)	NR	0.7	0.005	0.004	0.7	NR	<0.005	0.002
Riley	0.003	0.3	<0.0005	<0.001	<0.002	<0.001	<0.0005	0.0005
Foster Wheeler/ STOIC	0.120	6.9	<1	<2	<2	<0.004	0.0029	<0.060
Texaco (Ruhrkohle/Ruhrchemie)	<0.003	0.099	0.091	<0.001	0.009	<0.004	<0.0005	<0.001

Sources: Refs. 1-5, and 7.

[a] Values are in mg/L.

[b] <BC = Less than blank concentration.

[c] NR = Not reported.

TABLE D-10. SUMMARY OF CHEMICAL CONCENTRATIONS IN RCRA EP EXTRACTS OF CYCLONE DUSTS (mg/L)[a]

Element	Wellman-Galusha (Fort Snelling)[b]	Wellman-Galusha (Glen-Gery)	Riley	Texaco (Ruhrchemie)
Aluminum	>1	2	10	9.0
Antimony	0.008	0.03	0.005	<0.005
Arsenic	0.02	NR[c]	0.003	<0.003
Barium	1	0.7	.560/.300[d]	0.009
Beryllium	NR	0.003	<0.002	0.002
Cadmium	NR	0.005	<0.0005	0.091
Calcium	MC[e]	>10.0	620	64
Chromium	0.001	0.004	0.065/<.001[d]	<0.001
Cobalt	0.02	0.3	0.036	0.056
Copper	0.006	0.09	0.049	<0.001
Iron	0.6	1	0.024	0.031
Lead	0.008	0.7	<.002	0.009
Lithium	0.04	0.5	0.009	NR
Magnesium	MC	7	4.1	1.6
Manganese	0.1	>10	0.010	0.38
Mercury	NR	<0.0005	<.005	<0.0005
Molybdenum	0.002	0.07	0.11	0.003
Nickel	0.01	NR	0.066	0.37
Potassium	MC	>10	10	0.82
Selenium	0.006	NR	0.001	<0.004
Silicon	MC	2	0.24	9.7
Silver	NR	0.002	<0.0005	<0.001
Sodium	>3	>4	230	0.82
Strontium	1	NR	>10	NR
Titanium	0.05	0.2	0.140	<0.005
Vanadium	<0.001	0.002	0.100	<0.003
Zinc	0.07	>10	0.019	15

Sources: Refs. 2, 3, 4, and 7.

[a] Analyses by ICPES unless otherwise noted.

[b] Data by SSMS.

[c] NR = Not reported.

[d] ICPES data/AAS data.

[e] MC = Major component.

TABLE D-11. SUMMARY OF WATER QUALITY PARAMETERS FROM RCRA EP EXTRACTS OF CYCLONE DUSTS[a]

Parameter	Wellman-Galusha (Fort Snelling)	Texaco (Ruhrchemie)
Initial pH		
Chemical Oxygen Demand	1410	
Total Dissolved Solids	2281	270
Nitrate	<0.25	
Sulfite	<10	
Total Suspended Solids	16.7	
Ammonia	1.8	
BOD	3150	
Cyanide	0.05	
Thiocyanate		
Nitrate as N	<0.01	
Total Phosphate as P	0.2	
Phenol	0.038	0.023

Source: Refs. 2 and 7.

[a] Values are mg/L except for pH.

TABLE D-12. SUMMARY OF CHEMICAL CONCENTRATIONS IN AN ASTM EXTRACT OF A CYCLONE DUST (mg/L)[a]

Element	Riley
Aluminum	64
Arsenic	0.004
Barium	<0.001/0.39[b]
Beryllium	<0.002[c]
Boron	3.3
Cadmium	<0.0005
Calcium	32
Chromium	0.053/<0.001
Cobalt	0.036
Copper	0.045
Iron	0.012
Lead	<0.002
Lithium	<0.002[c]
Magnesium	0.46
Manganese	0.007
Mercury	<0.0005
Molybdenum	0.13
Nickel	0.044
Potassium	8.4
Selenium	0.002
Silicon	<0.020
Silver	<0.0005
Sodium	230
Strontium	3
Titanium	0.13
Vanadium	0.09
Zinc	.031

Source: Ref. 4.

[a] Analyses by ICPES, unless otherwise noted.

[b] ICPES data/AAS data.

[c] SSMS data.

TABLE D-13. SUMMARY OF WATER QUALITY PARAMETERS IN AN ASTM EXTRACT OF CYCLONE DUST[a]

Element	Texaco (Ruhrchemie)
Initial pH	8.61
Alkalinity as $CaCO_3$	620
Total Organic Carbon	60
Chloride	73
Total Dissolved Solids	24
Conductivity	1330
Nitrate	<0.5
Sulfate	<5
Odor (Threshold number)	1
Color (Pt -Co limit)	<5
Ammonia	210
Bromide	<0.1
Cyanide	0.08
Thiocyanate	8.4
Fluoride	9.4
Nitrate as N	<0.01
Total Phospate as P	0.02
Phenol	<0.018

Source: Ref. 7.

[a] Values are in mg/L except for pH, odor, and color.

TABLE D-14. ELEMENTS IN THE RCRA EXTRACT OF CYCLONE DUST FROM WELLMAN-GALUSHA (FORT SNELLING)

Element	Solids (mg/Kg)	EP Extract (mg/L)	Amount Leached (%)
Aluminum	7200	>1	≥0.3
Antimony	NR[a]	0.008	—[b]
Arsenic	<100	0.02	≥0.4
Barium	2300	1	0.9
Beryllium	0.4	NR	—
Cadmium	2	NR	—
Calcium	11300	MC[c]	—
Chromium	11	0.001	0.2
Cobalt	5	0.02	8
Copper	30	0.006	0.4
Iron	7900	0.6	0.2
Lead	<86	0.008	≥0.2
Lithium	6	0.04	13
Magnesium	12300	MC	—
Manganese	23	0.1	9
Mercury	NR	NR	—
Molybdenum	<49	0.002	0.08
Nickel	3	0.01	7
Potassium	NR	MC	—
Selenium	NR	0.006	—
Silicon	NR	MC	—
Silver	2	NR	—
Sodium	6200	>3	≥0.1
Strontium	1180	1	2
Titanium	317	0.05	0.3
Vanadium	<12	<0.001	≤0.2
Zinc	15	0.07	9

Source: Ref. 2.

[a] NR = Not reported.

[b] Dashes mean cannot be determined from available data.

[c] MC = Major component.

TABLE D-15. ELEMENTS IN THE RCRA EXTRACT OF CYCLONE DUST FROM WELLMAN-GALUSHA (GLEN-GERY)

Element	Solids (mg/Kg)	EP Extract (mg/L)	Amount Leached (%)
Aluminum	>1000	2	≤4
Antimony	53	0.3	11
Arsenic	83	NR[a]	--[b]
Barium	>1000	0.7	1.4
Beryllium	3	0.003	2
Cadmium	2	0.005	5
Calcium	>1000	>10	20
Chromium	58	0.004	0.1
Cobalt	10	0.3	60
Copper	68	0.09	3
Iron	>1000	1	≤2
Lead	230	0.7	6
Lithium	160	0.5	6
Magnesium	>1000	7	14
Manganese	570	>10	35
Mercury	NR	<0.005	--
Molybdenum	57	0.07	2
Nickel	47	NR	--
Potassium	>1000	>10	20
Selenium	16	NR	--
Silicon	>1000	2	≤4
Silver	5	0.002	0.8
Sodium	>1000	>4	8
Strontium	270	NR	--
Titanium	>1000	0.2	0.4
Vanadium	150	0.002	0.03
Zinc	>1000	>10	20

Source: Ref. 3.

[a] NR = Not reported.

[b] Dashes mean cannot be determined from available data.

TABLE D-16. ELEMENTS IN THE RCRA AND ASTM EXTRACTS OF CYCLONE DUST FROM RILEY

Element	Solids (mg/Kg)	EP Extract (mg/L)	Amount Leached (%)	ASTM Extract (mg/L)	Amount Leached (%)
Aluminum	>1000	10	≤20	64	26
Antimony	2	0.005	5	NA[a]	--[b]
Arsenic	19	0.003	0.3	0.004	0.08
Barium	>1000	0.300	0.6	0.39	0.2
Beryllium	0.7	<0.002	≤6	<0.002	1.1
Cadmium	<0.1	<0.0005	10	3.3	>100
Calcium	>1000	620	>100	<0.0005	0.0002
Chromium	26	<0.001	0.08	32	>100
Cobalt	2	0.036	36	<0.001	0.2
Copper	12	0.049	8	0.036	1.2
Iron	>1000	0.025	≤0.05	0.012	0.004
Lead	37	<0.002	0.1	<0.002	0.02
Lithium	10	0.009	1.8	NR[c]	--
Magnesium	>1000	4.1	8.2	<0.002	<4
Manganese	310	0.010	0.06	0.46	0.6
Mercury	NR	<0.005	--	0.007	--
Molybdenum	4	0.11	55	NR	--
Nickel	4	0.066	33	<0.0005	≤0.5
Potassium	>1000	10	20	0.003	
Selenium	3	0.001	0.7	0.13	18
Silicon	>1000	0.24	0.5	8.4	≤3.4
Silver	<0.1	<0.0005	10	0.002	8
Sodium	>1000	230	≤100	<0.0005	.002
Strontium	>1000	>10	20	230	≤92
Titanium	>1000	0.140	0.3	0.13	0.05
Vanadium	30	0.100	7	0.09	1.2
Zinc	60	0.019	0.6	0.031	0.2

Source: Ref. 4.

[a] NA = Not analyzed.

[b] Dashes mean cannot be determined from available data.

[c] NR = Not reported.

TABLE D-17. ELEMENTS IN THE RCRA EXTRACTS OF CYCLONE DUSTS FROM CHAPMAN AND FOSTER-WHEELER/STOIC

Element	Chapman			Foster Wheeler/STOIC		
	Solids (mg/Kg)	EP Extract (mg/L)	Amount Leached (%)	Solids (mg/Kg)	EP Extract (mg/L)	Amount Leached (%)
Arsenic	<0.4	0.02	≤100	40	0.120	6
Barium	500	<0.03	>100	320	6.9	4
Cadmium	NR[a]	<0.002	--[b]	3	<1	--
Chromium	30	<0.008	0.5	20	<2	≥100
Lead	60	<BC	--	870	<2	≥100
Selenium	NR	<0.002	--	10	<0.004	.8
Mercury	NR	NR	--	NR	0.0029	--
Silver	NR	0.002	--	690	<0.060	0.1

Source: Ref. 1 and 5.

[a] NR = Not reported.

[b] Dashes mean cannot be determined from available data.

TABLE D-18. ELEMENTS IN THE RCRA EXTRACT OF CYCLONE DUST FROM TEXACO (RUHRCHEMIE)

Element	Solids (mg/Kg)	EP Extract (mg/L)	Amount Leached (%)
Aluminum	83000	9	0.02
Antimony	8.2	<0.005	≤1
Arsenic	60	<0.003	≤0.1
Barium	455	0.009	0.04
Beryllium	19	0.002	0.2
Cadmium	13.2	0.091	14
Calcium	29000	64	4
Chromium	200	<0.001	0.01
Cobalt	38	0.056	3
Copper	71	<0.001	0.03
Iron	7.7	0.031	8
Lead	220	0.009	—[a]
Lithium	41	1.6	—[c]
Magnesium	6100	0.38	0.08
Manganese	380	<0.0005	0.002
Mercury	—		
Molybdenum	130	0.003	0.04
Nickel	130	0.37	6
Potassium	16000	0.82	0.1
Selenium	29	<0.004	0.3
Silicon	150000	9.7	0.1
Silver	0.61	<0.001	3
Sodium	7300	0.82	0.2
Strontium	310	NR[b]	—
Titanium	5600	<0.005	<404
Vanadium	140	<0.003	0.04
Zinc	1750	15	17

Source: Ref. 7.

[a] Dashes mean cannot be determined from available data.

[b] NR = Not reported.

APPENDIX E
DATA COMPILATION FOR GASIFIER TARS

TABLE E-1. SUMMARY OF SPARK SOURCE MASS SPECTROGRAPHIC ANALYSIS OF GASIFIER BY-PRODUCT TARS (g/Kg tar)

	Data Set		
Element	By-Product Tar (Chapman)	ESP Tar (Riley)	ESP Tar (Foster-Wheeler/STOIC)
Aluminum	NR[a]	0.5	>5
Antimony	80	0.09	0.01
Arsenic	<0.2	2	0.8
Barium	50	1	4
Bismuth	5	NR	0.03
Boron	1	0.4	0.02
Bromine	NR	0.1	0.1
Cadmium	<6	NR	NR
Calcium	NR	6	12
Cerium	5	NR	NR
Cesium	NR	0.02	0.06
Chlorine	NR	0.3	0.03
Chromium	50	0.03	0.6
Cobalt	NR	<0.1	<0.01
Copper	300	0.4	0.07
Fluorine	20[b]	1	4
Gallium	<9	0.04	0.07
Germanium	NR	0.06	<0.02
Iodine	5[c]	0.02	0.06
Iron	NR	0.9	MC[d]
Lanthanum	5	NR	0.05
Lead	50	0.2	0.4
Lithium	NR	0.04	0.03
Lutetium	NR	NR	NR
Magnesium	2000	1	0.2
Manganese	NR	0.02	0.6
Molybdenum	NR	0.1	0.02
Nickel	NR	0.08	0.09

(Continued)

TABLE E-1. (Continued)

Element	Data Set By-Product Tar (Chapman)	 ESP Tar (Riley)	 ESP Tar (Foster-Wheeler/STOIC)
Niobium	<5	NR	NR
Phosphorous	NR	3	0.8
Potassium	3000	3	6
Praseodymium	NR	<0.01	NR
Rubidium	0.5	0.02	0.01
Scandium	<1	<0.01	<0.01
Selenium	0.003	<0.03	<0.03
Silicon	NR	4	MC
Silver	NR	0.2	0.2
Sodium	NR	2	MC
Strontium	20	0.4	0.1
Sulfur	2000	8	7
Tin	NR	0.04	<0.02
Titanium	NR	0.6	0.3
Vanadium	1	0.2	<0.01
Yttrium	1	NR	NR
Zinc	NR	MC	2
Zirconium	NR	0.08	NR

Source: Refs. 1, 4, and 5.

[a] NR = Not reported.

[b] As F-

[c] As I-

[d] MC = Major component.

TABLE E-2. ELEMENTAL ANALYSIS OF GASIFIER BY-PRODUCT TARS BY SSMS (ug/g)

	Sasol (Tristates)							KRW Separator Pit Sludge Solids[b]		
	Medium Heavy Tar[a]	Heavy Tar[a]	Bulk Heavy Tar[a]	Recycle Tar[a]	Lt. Tar[a] 24 Hr	Lt. Tar[a] 48 Hr	Site[a] Tar	WY Subbituminous	Pittsburgh #8	ND Lignite
Aluminum	1400	1600	620	130	30.5	24	25	3.40%	1.70%	1.25%
Antimony	9.7	6.3	5.7	4.8	4.0	1.6	0.8	ND(0.3)[c]	0.7	0.8
Arsenic	34	30	18	26	30	14.2	4	18	22	14
Barium	260	170	470	29	9.4	2.3	27	1300	270	700
Beryllium	0.24	<0.094	<0.088	<0.099	<0.83	<0.086	0.1	3.9	1.3	1.2
Boron	NR[d]	NR	NR	NR	NR	NR	NR	20	80	70
Cadmium	4.5	3.1	2.4	3.5	2.6	1.0	ND	0.47	2.7	1.2
Calcium	1500	1420	1500	570	430	340	630	4.40%	6200	4.0%
Chromium	22	10	29	<0.21	<0.17	<0.18	ND	41	39	32
Cobalt	<1.3	<1.2	<1.1	<1.2	<1.0	<1.1	5	13	9.5	6.0
Copper	<0.21	<0.20	<0.18	<0.21	<0.17	<0.18	3	66	17	22
Iron	1600	1800	320	200	120	29	120	2.2%	1.30%	1.40%
Lead	29	16	15	23	16	6.5	10	18	17	10
Lithium	11	<0.085	9.7	<0.089	5.6	<0.077	4	12	22	7.8
Magnesium	500	380	480	<7.0	25	<7.0	23	8800	1100	1.0%
Manganese	6.0	6.7	2.9	0.26	33	<0.20	0.9	120	36	120
Mercury	0.55	0.49	0.68	1.2	0.49	0.22	0.12	0.27	0.25	0.10
Molybdenum	4.7	1.0	1.7	<0.41	<0.34	<0.36	1	3.6	4.8	4.7
Nickel	1.9	1.7	0.55	<0.62	<0.52	<0.54	5	35	19	12
Phosphorus	NR	NR	NR	NR	NR	NR	NR	920	640	880
Potassium	370	440	280	<8.7	<10	<8	100	1400	2500	2400
Selenium[a]	1.5	1.2	0.83	<0.60	1.2	1.6	ND	6.0	1.5	1.4
Silicon	1800	4400	4800	ND	400	36	170	NR	2.40%	1.30%
Silver[a]	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	ND	ND(0.17)	NM[e]	NM
Sodium	2500	1900	350	220	750	<1.0	ND	2100	8000	1.10%
Strontium	6.9	6.5	6.5	0.32	<0.081	0.30	10	880	410	1800
Titanium	112	100	27	<1.0	<0.86	7.2	29	NC(1)	ND(1)	ND(1)
Thallium	NR	NR	NR	NR	NR	NR	NR	2300	1400	720
Uranium	NR	NR	NR	NR	NR	NR	NR	ND(6)	ND(6)	ND(6)
Vanadium	7.7	<0.59	<0.55	<0.62	<0.52	<0.54	0.8	81	52	28
Zinc	22	17	15	14	16	3.1	7	130	0.72	82

[a] Source: Ref. 15
[b] Source: Ref. 8
[c] ND = Not detected (detection limit).
[d] NR = Not reported.
[e] NM = Not measured.

TABLE E-3. ATOMIC ABSORPTION DATA FOR THE LURGI-TYPE (KOSOVO) LIGHT TAR

Component	Overall Value (mg/L)
Trace Elements	
As	18
Be	0.10
Cd	0.70
Co	ND[a]
Cr	3.2
Cu	17
Hg	ND
Mo	ND
Ni	9.5
Pb	7.2
Sb	ND
Se	1.7
Sr	21
Tl	0.42
V	0.53
Zn	30

Source: Ref. 6.

[a] ND = Not detected.

TABLE E-4. SUMMARY OF TEST RESULTS OF BY-PRODUCT TAR FROM CHAPMAN

Category	Estimated Concentration (ug/g of tar)
1. Aliphatic Hydrocarbons (Nonanes, Heptanes) A. Alkanes and Cyclic Alkanes Alkanes, C_{10}-C_{18}	1×10^5
2. Halogenated Aliphatic Hydrocarbons (Lindane) A. Saturated Alkyl Hydrocarbons Methyl Chloride	4×10^4
3. Ethers	ND[a]
4. Halogenated Ethers	ND
5. Alcohols	ND
6. Glycols, Epoxides	ND
7. Aldehydes, Ketones	ND
8. Carboxylic Acids and Their Derivatives (Phthalates) D. Esters Aliphatic Esters Phthalate Esters	4×10^4
9. Nitriles	ND
10. Amines (Methyl Anilines, Aminonaphthalene) C. Aromatic Amines and Diamines Aniline, alkyl series	6×10^4
11. Azo Compounds and Hydrazine Derivatives	ND
12. Nitrosamines	ND
13. Thiols	ND
14. Sulfonic Acids, Sulfoxides	ND
15. Benzene, Substituted Benzene Hydrocarbons (Indene, Alkyl Benzene) Benzene, alkyl series	4×10^4

(Continued)

Table E-4. (Continued)

Category	Estimated Concentration (ug/g of tar)
16. Halogenated Aromatic Hydrocarbons	ND
17. Aromatic Nitro Compounds	ND
18. Phenols (all listings)	
A. Monohydrics	8×10^4
Phenol, alkyl series	
19. Halophenols	ND
20. Nitrophenols	ND
21. Fused Aromatic Hydrocarbons and Their Derivatives (Dibenz(a,h)anthracene)	3×10^5
Acenaphthene, alkyl series	
Acenaphthalene, alkyl series	
Anthracene, alkyl series	
Benzopyrene, alkyl series	
Chrysene, alkyl series	
Coronene, alkyl series	
Naphthalene, alkyl series	
Phenanthrene	
Pyrene, alkyl series	
22. Fused Non-Alternate Polycyclic Hydrocarbons	TR[b]
Fluoranthene	

(Continued)

Table E-4. (Continued)

Category	Estimated Concentration (ug/g of tar)
23. Heterocyclic Nitrogen Compounds (Dibenzo(c,d)carbazole)	2×10^5
A. Fused Six-Membered Ring Heterocycles Quinoline, alkyl series	
C. Pyrrole and Fused Ring Derivatives of Pyrrole Carbazole, alkyl series	
24. Heterocyclic Oxygen Compounds (Tetrahydrofuran) Benzonaphthofuran	1×10^5
25. Heterocyclic Sulfur Compounds (Benzonaphthothiophene)	1×10^5
26. Organometallics	ND
27. Lithium	ND
28. Sodium	ND
29. Potassium	3×10^3
30. Rubidium	0.5
31. Cesium	ND
32. Beryllium	ND
33. Magnesium	2×10^2
34. Calcium	ND
35. Strontium	20
36. Barium	50
37. Boron	1
38. Aluminum	ND

(Continued)

Table E-4. (Continued)

Category	Estimated Concentration (ug/g of tar)
39. Gallium	<9
40. Indium	ND
41. Thallium	ND
42. Carbon	ND
43. Silicon	ND
44. Germanium	ND
45. Tin	ND
46. Lead	50
47. Nitrogen	ND
48. Phosphorus	ND
49. Arsenic	<0.2
50. Antimony	80
51. Bismuth	5
52. Oxygen (as O_3)	ND
53. Sulfur	2×10^3
54. Selenium	3×10^{-3}
55. Tellurium	ND
56. Fluorine (as F^-)	20
57. Chlorine (as Cl^-)	ND

(Continued)

Table E-4. (Continued)

Category	Estimated Concentration (ug/g of tar)
58. Bromine (as Br^-)	ND
59. Iodine (as I^-)	5
60. Scandium	<1
61. Yttrium	1
62. Titanium	ND
63. Zirconium	ND
64. Hafnium	ND
65. Vanadium	1
66. Niobium	<5
67. Tantalum	ND
68. Chromium	50
69. Molybdenum	ND
70. Tungsten	ND
71. Manganese	ND
72. Iron	ND
73. Ruthenium	ND
74. Cobalt	ND
75. Rhodium	ND
76. Nickel	ND

(Continued)

Table E-4. (Continued)

Category	Estimated Concentration (ug/g of tar)
77. Platinum	ND
78. Copper	300
79. Silver	ND
80. Gold	ND
81. Zinc	ND
82. Cadmium	<6
83. Mercury	6×10^{-2}
84. Lanthanides	ND
Lanthanum	5
Cerium	5
Praseodymium	
Neodymium	
Samarium	
Dysprosium	
85. Actinides	ND
Uranium	
Thorium	

Source: Ref. 1.
[a]ND = not determined.

TABLE E-5. SUMMARY OF PROXIMATE/ULTIMATE ANALYSIS OF GASIFIER BY-PRODUCT TARS[a]

	Chapman	Riley	Lurgi-Type (Kosovo)[b]	KRW- WY Subbituminous	KRW- Pittsburgh #8
Weight Percent (DAF)					
Carbon	77.30	58.57	82	54.32	71.73
Hydrogen	6.06	8.40	8.4	2.05	0.42
Nitrogen	1.42	0.69	1.3	0.50	0.50
Sulfur	0.52	0.33	1.3	0.85	1.57
Oxygen (by diff.)	–[c]	30.75	7.8	0.72	0.68
Chlorine	–	–	–	0.08	0.04
Weight Percent (As Received)					
Volatiles	–	96.66	–	9.7	2.81
Fixed Carbon	–	3.14	–	31.7	71.33
Ash	0.97	0.20	0.49	29.34	24.79
Moisture	–	–	1.1	29.26	1.07
Heating Value					
Kcal/Kg (Btu/lb)	–	6256(11,261)	6340(11,412)	4356(7840)	5867(10,560)
Sulfur Forms					
Pyritic	–	–	–	–	0.11
Sulfate	–	–	–	–	0.10
Organic	–	–	–	–	1.97
Total Sulfur	–	–	–	–	2.18

Source: Refs. 1, 4, 6, and 8.

[a] Values are in % except for heating value.

[b] Average values for all process tars.

[c] Dashes mean no data available.

TABLE E-6. TEST DATA FOR BY-PRODUCT SAMPLE POINT 13.9, LIGHT TAR FROM LURGI-TYPE (KOSOVO) GASIFIER[a]

Component	Overall Value[b]	Range
Specific Gravity	1.06	
High Heating Value, Kcal/Kg (Btu/lb)	8910 (16,040)	8710-9810 (15,680-17,660)
Low Heating Value, Kcal/Kg (Btu/lb)	8280 (14,905)	
Ultimate Analysis (wt %)		
Carbon	82	72-82
Hydrogen	8.4	8.1-8.4
Nitrogen	1.3	
Sulfur	0.49	0.49-0.75
Ash	0.22	0.22-0.92
Chlorine	-[c]	
Oxygen (Difference)	7.8	
Moisture	1.1	

Source: Ref. 6.

[a] Single source values.

[b] Values are best values from available data.

[c] No data available.

TABLE E-7. INFRARED SPECTRAL COMPOSITION OF A SITE TAR

Fraction Number	Composition (Functional groups present)	Relative Percent In Extract
1	Aliphatic hydrocarbons ($-C_{H2}-$) >4 some branched	0.27
2	Substituted aromatic with alkyl and branched alkyl substituents	1.96
3	Substituted aromatic with alkyl and branched alkyl substituents	17.28
4	Same as above plus NH stretch	8.39
5	Same as above but probably OH stretch, trace C=O	7.32
6	Bonded OH and NH stretch	52.37
7	Primary OH, water of hydrocarbon, CO either, ester (acetate), split carbonyl (possible acid)	4.98
8	Split C=O, (acid and ester), water of hydration, possible ester (acetate), aliphatic, methyl group	7.43

Source: Ref. 19.

TABLE E-8. POLYNUCLEAR AROMATIC DATA FOR THE HEAVY TAR FROM THE LURGI-TYPE (KOSOVO) GASIFIER

Component (mg/kg tar)	Overall Value (mg/kg tar)
Benz(a)anthracene	500
7,12-Dimethylbenz(a)anthracene	1300
Benzo(b)fluoranthene	320
Benzo(a)pyrene	240
3-Methylcholanthrene	ND[a]
Dibenz(a,h)anthracene	14
252 Group (as Benzo(a)pyrene)	1000

Source: Ref. 6.
[a] Not detected.

TABLE E-9. POLYNUCLEAR AROMATIC HYDROCARBON DATA FOR THE LIGHT TAR (13.9) FROM KOSOVO

Component	Overall Value [a]
Benz(a)anthracene	490
7,12-Dimethylbenz(a)anthracene	1100
Benzo(b)fluoranthene	310
Benzo(a)pyrene	210
3-Methylcholanthrene	26
Dibenz(a,h)anthracene	23
252 Group (as benzo(a)pyrene)	950

[a] Analysis by GC/MS-liquid crystal.

TABLE E-10. PHENOL SPECIATION DATA FOR THE LIGHT TAR (13.9) FROM KOSOVO

Component (mg/g)	Overall Value[a]	Retention Time
Phenol	5.9	8.55
o-Cresol (as Phenol)	4.9	9.50
m-Cresol	13	9.70
p-Cresol (as Phenol)	1.4	9.90
2,6-Dimethylphenol	1.2	10.10
2,4-Dimethylphenol	7.5	10.50
3,4-Dimethylphenol	3.9	10.95
1-Naphthol	1.0	13.20
Unknowns (as Phenol)		
	1.3	10.35
	10.1	10.65
	2.1	11.20
	3.7	11.30
	3.3	11.45
	2.8	11.60
	4.3	11.70
	2.6	12.35
	2.7	12.40
Other unknowns (as Phenol)[b]	94	-

[a] Analysis by GC/FID.
[b] Summation of all other unknown peaks.

TABLE E-11. PHENOL SPECIATION DATA FOR THE HEAVY TAR (13.8) FROM KOSOVO GASIFIER

Component (mg/g)	Overall Value[a]	Retention Time
Phenol	3.3	8.55
o-Cresol (as Phenol)	2.4	9.50
m-Cresol	6.7	9.70
p-Cresol (as Phenol)	0.70	9.90
2,6-Dimethylphenol	0.57	10.10
2,4-Dimethylphenol	3.6	10.50
3,4-Dimethylphenol	2.0	10.95
1-Naphthol	0.69	13.20
Unknowns (as Phenol)		
	0.61	10.35
	5.4	10.65
	0.98	11.20
	1.7	11.30
	1.9	11.45
	1.4	11.60
	1.8	11.70
	1.2	12.35
	1.2	12.40
Other Unknowns (as Phenol)[b]	81	-

[a] Analysis by GC/FID.
[b] Summation of all other unknown peaks.

TABLE E-12. TAR VISCOSITY DATA[a]

Sample	Temp °F	CS	SUS
Oil	100	46.1,46.0	214,213
	140	13.7,13.4	72.9,71.8
Light Tar 24-Hour Grab	100	42,6,45.6	198,212
	140	13.6,13.6	72.9,72.3
Light Tar 48-Hour Grab	100	56.1,57.6	269,267
	140	15.9,15.8	81.4,80.9
Medium-Heavy Tar	100	12.6,12.1	584,561
	140	27.8,26.0	132,124
Heavy Tar	100	64.6,67.5	300.313
	140	17.5,18.1	87.8,90.3

CS = Centistokes
SUS = Saybolt Universal Seconds
Duplicate samples analyzed

[a] Winton, S.L., M.P. Kilpatrick, J.S. Gibson and W.R. Menzies. Export Sample Program; Analytical Results for Samples Obtained during Tri-States Synfuel's Coal Test at Sasol One. Prepared by Radian Corporation, November 1982.

TABLE E-13. SUMMARY OF RESULTS OF IN VITRO TOXICITY TESTS

Sample	Description	Test System	Toxicity (EC_{50})
2373L	ASTM heavy tar leachate	CHO[a]	Low toxicity (120 μl/mL)
2472	Tar	CHO	High toxicity (0.034 μl/mL)
2473	Heavy tar and dust	CHO	High toxicity (0.072 μl/mL)

[a] Chinese Hampster Ovary Test.

TABLE E-14. SUMMARY OF RESULTS OF AMES ASSAY OF KOSOVO BY-PRODUCTS

2472 - Tar (Solvent-Exchanged with DMSO)[a]

There was a positive response with TA-1538 at 0.02 μl/plate without metabolic activation and beginning with 0.01 μl/plate (the lowest concentration tested) with metabolic activation. There was also a positive response with TA-98 with metabolic activation beginning with 0.015 μl/plate. The highest concentration tested (0.025 μl/plate) caused a slight toxic effect to the lawn of all the strains.

2473 - Heavy Tar and Dust (Solvent-Exchanged with DMSO)[a]

There was a positive response with TA-98 with metabolic activation at 0.02 μl/plate and with TA-1538 with metabolic activation at 0.01 μl/plate.

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[a] Volatile samples 2472 and 2473 were solvent-exchanged with DMSO. Solvent-exchanged samples contained highly volatile components and were tested in the Ames assay under special handling conditions. Each set of plates for each concentration tested was placed in a Ziploc bag before being placed in an incubator for the 48-hour incubation period. Corresponding positive and negative controls for these assays were handled in the same manner. All four volatile, solvent-exchanged samples showed overall slight toxicity at all concentrations and for all strains. Bacterial colonies in all plates which are held in plastic bags (including those in control dishes) are smaller than normal due perhaps to the lack of oxygen under such assay conditions. Additionally, colonies in dishes treated with volatile samples were smaller than their corresponding controls. Strain TA-100, treated with all four samples in the presence of metabolic activation, gave abnormal spreading colonies indicative of cell membrane disruption.

TABLE E-15. AMES ASSAY IV, SAMPLES 32473--HEAVY TAR AND DUST

	Revertants Per Plate[a]									
	TA-98		TA-1537		TA-1538		TA-100		TA-1535	
	-S9	+S9	-S9	+S9	-S9	+S9	-S9	+S9	-S9	+S9
Control (DMSO)	17 ± 3	21 ± 1	9 ± 0	10 ± 2	10 ± 1	14 ± 2	96 ± 4	106 ± 2	12 ± 2	15 ± 1
2-Anthramine[b] (10 ug/plate)	16 ± 1	256 ± 17	8 ± 1	31 ± 1	16 ± 5	288 ± 31	89 ± 6	5416 ± 25	10 ± 1	40 ± 7
Daunomycin[c] (10 ug/plate)	>500	>500								
9-Aminoacridine[d] (50 ug/plate)			46 ± 4	60 ± 1						
2-Nitrofluorene[b] (10 ug/plate)					239 ± 8	222 ± 4				
Methylmethane sulfonate[b] (50 ug/plate)							225 ± 9	188 ± 6		
N-Methyl-N'-nitro-N-nitrosoguanidine[b] (50 ug/plate)									2445 ± 134	2051 ± 58
#2473 - Heavy Tar and Dust[b]										
(0.01 ul/plate)	11 ± 0	31 ± 3	5 ± 1	9 ± 1	6 ± 1	30 ± 1	96 ± 0	89 ± 8	9 ± 0	8 ± 1
(0.015 ul/plate)	24 ± 1	31 ± 2	5 ± 1	11 ± 1	8 ± 0	55 ± 6	98 ± 15	95 ± 1	10 ± 1	11 ± 0
(0.02 ul/plate)	8 ± 1	60 ± 6	5 ± 1	8 ± 2	9 ± 1	62 ± 2	85 ± 2	79 ± 3	5 ± 2	8 ± 2
(0.025 ul/plate)	9 ± 0	82 ± 3	5 ± 1	12 ± 1	6 ± 1	66 ± 2	94 ± 1	87 ± 2	3 ± 1	3 ± 0
#1152A - Light Oil[b]										
(0.01 ul/plate)	11 ± 1	14 ± 1	4 ± 1	6 ± 1	8 ± 2	10 ± 1	73 ± 2	64 ± 1	8 ± 1	6 ± 0
(0.015 ul/plate)	9 ± 1	18 ± 1	4 ± 0	5 ± 1	7 ± 1	14 ± 2	62 ± 2	66 ± 1	7 ± 2	7 ± 2
(0.02 ul/plate)	8 ± 1	16 ± 1	6 ± 1	7 ± 1	12 ± 1	15 ± 3	67 ± 5	47 ± 1	10 ± 2	6 ± 0
(0.025 ul/plate)	10 ± 1	11 ± 1	4 ± 1	6 ± 1	6 ± 1	10 ± 0	88 ± 7	81 ± 11	10 ± 2	5 ± 1

[a] Mean of 2 replicate plates ± standard error of the mean.

[b] Dissolved/diluted in dimethylsulfoxide (DMSO).

[c] Dissolved in sterile distilled water.

[d] Dissolved in 95% ethanol.